

Cognitive, Cardiovascular and Muscular Stress Imposed by a Twenty20 Batting Simulation

by

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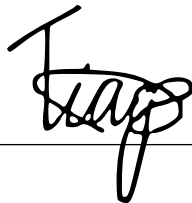
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Declaration of Authorship

I, Tiago Lopes, declare that this Thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signed:

A handwritten signature in black ink, appearing to read 'Tiago', written over a horizontal line.

Date: 23-Sep-2024

Abstract

In the sport of cricket, batting requires prolonged cognitive control accompanied with high muscular and cardiovascular stress. However, the acuity of information processing (cognition) during bouts of physical activity is not fully studied. This investigation is the first to investigate the influence of striking rare in Twenty20 cricket on the physiology of the batter.

Phase 1 a retrospective analysis of competitive individual innings in Twenty20 matches between 2006–2019. Per-delivery probabilities of run type and on/off-strike demarcation were calculated for two innings subsets. Both simulations replicate a 1-hour and 2-minute partnership of 93 deliveries, 51 of which are ‘on-strike’. The low strike rate innings replicates scoring 61 runs, compared to 88 runs in the high strike rate innings.

Phase 2, a randomised, repeated measures laboratory design, recruited 14 skilled batters (competitive playing experience > 6 years) to perform both simulations. The physical (heart rate, muscular output, blood lactate accumulation, fluid loss) and cognitive (working memory, executive functioning, prefrontal cortex haemodynamics) strain of Twenty20 batting was quantified. High strike rate batting was found to augment responses of heart rate ($p < 0.01$), and produce slower sprint performance ($p < 0.01$). However, changes to lower-limb peak power output ($p = 0.08$), fluid loss ($p = 0.71$) and accumulation of blood lactate ($p = 0.67$) were comparable. Working memory response times improved with moderate effects ($d = 0.61$) in the low strike rate simulation. Compared to large effects following the high strike rate simulation ($d = 1.20$) where executive functioning was moderately more error-prone ($r = 0.60$). The prefrontal cortex displays substantially less reserve to increase concentrations of oxygenated haemoglobin when confronted with cognitively demanding tasks following either simulation.

In **Phase 3**, a novel device (Pitch Reaction Test - PRT) is developed to ecologically quantify response times of implicit and explicit information processing. The recording accuracy of the PRT was assessed using a high-speed camera. Overall, a strong relationship is observed between video footage and PRT responses ($\beta = 0.99 - 0.97$). Neither subject height ($\beta = -0.01$, $p = 0.54$) or true leg length ($\beta = 0.00$, $p = 0.58$) were significant predictors of PRT performance. Future studies should continue to elucidate how batting modulates information processing efficiency.

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Journal Submissions Emanating from Work Presented in this Thesis

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Lopes T, Goble D, Olivier B and Kerr S. The Physicality of a Twenty20 Batting Innings is Moderately Affected by Strike Rate. (submitted) to journal of [redacted]

Lopes T, Goble D, Kerr S and Olivier B. Speed-accuracy trade-offs are Augmented at Higher Strike Rates in Experienced Batters. (submitted) to journal of [redacted]

Lopes T, Kerr S and Olivier B. Pitch Reaction Test – Measuring Cognitive Function of Cricket Batters on the Field. (submitted) to journal of [redacted]

Introduction

The objective of a cricket match is to score more runs than the opposing team. In separate halves, called an innings, batters compete against the opposing team's bowlers and fielders to accumulate a competitive run total. Runs are scored by intercepting a bowlers' deliveries into gaps in the field, allowing the batting pair to run one, or more, lengths of the pitch (17.68m) before the ball is retrieved. And 'boundaries', which are struck outside the field of play either, aerially directly out of play (six runs) or, touch the field before leaving play (four runs). Therefore, the bowling and fielding team tactfully align the positioning of fielders with planned delivery characteristics, to restrict the batter's attainable strokes and run scoring options.

Run scoring can also be limited when batters are 'dismissed' through various modes. Namely, a delivery which strikes the stumps and dislodges the bails or, makes direct contact with the batter's legs but is deemed to have a trajectory that would strike the stumps. Second, fielders may retrieve and return intercepted deliveries to the stumps before batters complete attempted runs and reach a safe zone called the crease. Finally, intercepted deliveries which are yet to contact the field of play can be caught by fielders, including a specialist fielder behind the stumps, or the bowler. A dismissed batter is replaced by the teammate next in the batting line-up until all players are dismissed and a batting pair can no longer be formed ('bowled out'). Batters therefore need to equate the risk of run scoring with the risk of being dismissed, and teams need a balance of specialist batters and bowlers. At the completion of the first innings a run target is set, and teams reverse roles to defend or chase the set run total in the following innings.

Innings duration is largely dependent on the format of the match. International competition is comprised of three formats, broadly categorised as limited or unlimited overs cricket (one over = six legal deliveries). 'Test' matches are played over five days, 90 overs per day, with an unlimited number of overs per innings to achieve a competitive run total. The objective is to set a run target large enough to bowl out the opposing team before the target is reached. Each team, however, has two opportunities (innings) to bat and bowl and a result is only achieved if the aggregated run target is not met and a team is bowled out twice within the five days of play. An individual bowler is also not restricted to a maximum number of overs in an innings/match and one team innings can be prolonged to three (or more) days. Accumulating a run total large

enough to very likely not be reached by the opposing team in the remaining time, and if not bowled out twice, the match is drawn. In limited overs cricket, a team innings is restricted to 50 overs in One Day Internationals (ODI's) or, 20 overs in the Twenty20 format. A single bowler is restricted to ten overs in ODI's and four in Twenty20's and the positioning of fielders is also regulated throughout the innings. A minimum of four fielders must remain within the inner ring (30m diameter) throughout an innings. And during overs called the 'PowerPlay', only two fielders can be placed outside the inner ring protecting the boundary rope (ICC [2021](#)).

Plainly then, the difference between unlimited and limited overs cricket, is the balance between the risk of run scoring and the risk of being dismissed. In limited overs cricket, there are less deliveries available to bowl out a team in the innings, but also less deliveries to achieve a competitive run total. Batters therefore place less emphasis on the risk of being dismissed and rather consider the rate at which runs can be scored. Exemplified further when considering Twenty20's vs ODI's where a team innings is restricted to 120 vs 300 deliveries. The emphasis on run scoring intensity (strike rate) compared to risk of dismissal is further shifted to favour high-risk, high reward batting.

The differences in tactics and innings duration between formats expectedly modulate the physical workload of the innings. A five-day Test match can be summarised as an intermittent endurance-volume activity (Petersen et al. [2010](#)). In large contrast to the intermittent, but high-intensity 2-hour innings of Twenty20 cricket (Petersen et al. [2010](#); Vickery et al. [2018](#)). Therefore, different match formats should be assessed individually to fully grasp an athlete's responses and the underlying determinants of success. The art of batting has received little attention in literature, and to date, fewer studies have specifically investigated batting in Twenty20 cricket.

Aims and Objectives

This investigation will aim to quantify the physical (cardiovascular and muscular) and cognitive load imposed by a simulated Twenty20 batting innings. To address this aim, the objectives of the study are to -

1. Develop two Twenty20 simulations of equal duration which replicate match play of an individual innings for a 1) high scoring and 2) low scoring innings.
2. Assess and quantify the physical and muscular strain imposed by the simulations by measuring changes in muscular output, muscle energy substrate metabolism and psychophysical load.

3. Quantify the cognitive workload experienced before and after each simulation by measuring haemodynamic changes in the prefrontal cortex and the performance responses of batters.
4. Assess changes in working memory and executive function performance imposed by the simulations.
5. Develop a novel device to measure visual attention and psychomotor function in a form which is ecologically congruent with batting.
6. Investigate the measuring accuracy and reliability of response times obtained from the novel device in (5) – Pitch Reaction Test

The thesis follows an integrated format. The physicality and cognitive components of run scoring are presented in a review of literature. The following chapters are original articles which provide results to the aims of the investigation. Linking notes between results chapters are included to summarise key findings and provide rationale for subsequent chapters. A final discussion chapter integrates novel findings with broader scientific theories and describes how findings can be integrated into practice.

Chapter 1

Physiological Description of a Batting Innings - Review of Literature

Intercepting a high-velocity cricket ball requires a combination of precise neuromuscular control and decision making (Sarpeshkar and Mann [2011](#); Scanlan et al. [2016](#)). Hence, a batter's mental processes (cognition) of selecting and coordinating proper responding movements/strokes under extreme temporal constraints. Combined with considering broader match context and run scoring strategies throughout an innings. The cognitive determinants of batting success should not be disregarded. Furthermore, the physical cost of run scoring in a prolonged innings, requires advanced aerobic and anaerobic adaptations or fitness (Noakes and Durandt [2000](#); Scanlan et al. [2016](#)). A batting innings, therefore, provides a compelling model of the interaction between physical stress and cognitive functioning. Enveloped in a competitive, performance environment.

This review will attempt to unpack this interaction in turn, first addressing the physical load of batting. Second, the cognitive requirements of successful batting and their functional domains in the brain will be discussed. Third, the interactive, bidirectional effect of sustained physical stress on cognitive functioning, and sustained cognitive stress on physical performance. Finally, to fully investigate the exercise-cognition interaction specific to Twenty20 cricket, simulating the competitive sporting environment in controlled laboratory settings is beneficial. While assessments which quantify cognitive function specific to the mental processes of batting are required and these methods will also be reviewed.

1.1 The physical demands of run scoring

When considering the physical and physiological stress of exercise, several variables moderate the overall stress imposed by an activity. Duration, intensity, and environmental factors influence the physiological responses of the exerciser (Laforgia, Withers, and Gore [2006](#); Brotherhood [2008](#)) and therefore inform the workload placed on the batter. A seminal investigation by Noakes and Durandt ([2000](#)) described the activity

profile of a batting innings to be of comparable durations to endurance-volume sports. But, unlike endurance-volume activity, batting produces an intermittent activity profile with periods of high-intensity, randomly dispersed among recovery periods of lesser intensity (Noakes and Durandt [2000]; Petersen et al. [2011]; Vickery et al. [2018]). Noakes and Durandt ([2000]) estimated that in an individual ODI innings scoring 100 runs, the batter covers 3.6km in 8 minutes running between the wickets - an average speed of $24\text{km} \cdot \text{h}^{-1}$ (Noakes and Durandt [2000]).

Petersen et al. ([2010]) supplied more direct insight to movement patterns with GPS tracking of batters, fielders, and bowlers in different formats. Overall, the hypothesis that the duration and intensity of an individual batting innings would be moderated by match format was confirmed. Test cricket produced individual innings with longest durations and work:rest ratios of 1:61 - allowing the longest recovery periods between high-intensity bouts (Petersen et al. [2010]; Petersen et al. [2011]). Followed by ODI's where work:rest ratios are tightened to 1:50. And a Twenty20 innings proving to be most intense (1:38) but, of the shortest overall duration (Petersen et al. [2010]). Therefore, a divergent relationship is apparent where the shortest individual innings duration of Twenty20 cricket produces the most high-intensity efforts per hour (15 ± 9 high-intensity efforts $\cdot \text{h}^{-1}$). Compared to high intensity efforts per hour in ODI's (13 ± 9) and Tests (8 ± 3) where as innings duration increases, high-intensity efforts become more dispersed (Petersen et al. [2010]). Collectively it can be concluded that the prolonged duration of a batting innings imposes aerobic metabolic stress on the batter (De Feo et al. [2003]; Green et al. [2013]). It is therefore conceivable that run scoring rates moderate the intensity and anaerobic stresses of batting (De Feo et al. [2003]; Green et al. [2013]). Thus, to quantify the physical stress of batting, the metabolic (aerobic and anaerobic) and local/muscular cost of an innings should be considered.

1.1.1 Musculoskeletal variables of batting performance

A primary component of run scoring is sprinting the length of the pitch (17.68m), referred to as running between the wickets. This process can be further dissected into phases. First, the batter transitions from the upright, side-on posture of ball-striking into maximal sprint acceleration. Being relatively stationary at bat-ball impact, the batter must overcome this inertia and thus, the magnitude of acceleration achieved in the primary strides is paramount to performance over the short distance. The batter must optimise the horizontal forces applied to the ground through the lower extremities while minimising vertical forces, which will perform no work in the intended

direction of travel (Kugler and Janshen [2010](#)). Therefore, from the posture of ball-striking, the batters' center of mass must be lowered, and positioned in front of the desired position of foot-ground contact (Morin et al. [2015](#)). Ultimately increasing the horizontal forces which can be applied through extension of the hip, knee, and ankle plantarflexes (Kugler and Janshen [2010](#)).

Accelerative performance will be determined by the rate at which energy can be transferred from mechanical tension in muscle fibres to horizontal velocity. Peak acceleration is achieved when braking forces are counterbalanced well-below propulsive forces (Kawamori, Nosaka, and Newton [2013](#); Morin et al. [2015](#)). Therefore, the horizontal force applied to the ground must be achieved from minimal contact time between foot-ground (Kawamori, Nosaka, and Newton [2013](#); Morin et al. [2015](#)). Following acceleration, the next phase of a run can be described as the crossover between increasing velocity and achieving maximum velocity (V_{max}) for the given run. In this phase, the batter transitions from the forward-lean of maximal accelerative strides to an upright posture where hip and knee extension can be maximised in the pursuit of increased stride length (D. Johnson and Buckley [2001](#); Kugler and Janshen [2010](#)). Last, the batter approaches the opposite crease, cognizant of maximising the time/distance spent at V_{max} and therefore withholding decelerative efforts to the final strides. The maximal deceleration conversely requires centre of mass to be lowered and placed behind the desired position of foot-ground contact, to maximise the application of horizontal force applied opposing the direction of travel/inertia (Morin et al. [2015](#)). If more runs are available, the batter decelerates while completing a 180° turn and subsequently accelerates maximally to the returning crease.

In summary, considerable forces are required to overcome the batter's inertia throughout phases of the run (Kawamori, Nosaka, and Newton [2013](#); Morin et al. [2015](#)). And emphasis is placed on the rate of force production (Kawamori, Nosaka, and Newton [2013](#)), as running between the wickets is temporally contested against opposing fielders. The body-position and balance of the batter at ball-contact further complicates the transition from ball-striking to sprinting. For example, 'short' deliveries are intended to bounce distally from the batter and climb to shoulder-head height. To intercept a short delivery, the batter attempts to negate the balls' steep trajectory by stepping backwards towards the stumps, extending at the knees and into plantar flexion – reaching to maximise the attainable height of interception. Adopting the posture necessary to be in control of the stroke and 'on top of the bounce', obliges the batter to move body mass in the opposite direction of upcoming accelerative efforts (Kugler and Janshen [2010](#)).

Horizontal velocity must then be achieved, near instantaneously, in the intended direction from maximal power output in the initial strides (Kawamori, Nosaka, and Newton 2013). Lower-limb peak power output (PPO) therefore describes a batter's ability to overcome inertia, demonstrated in previous sprint performance studies (Bissas and Havenetidis 2008; Seitz et al. 2014). In a prolonged batting innings however, resistance to decaying PPO from repeated efforts i.e., fatigue (Girard, Mendez-Villanueva, and Bishop 2011), may be equally important to batting performance.

Repeated accelerative and decelerative events are known to reduce running performance (Highton, Twist, and Eston 2009; Morin, Dupuy, and Samozino 2011). Noakes and Durandt (2000) estimate that to score a century of runs, a batter would produce 110 decelerative efforts. Christie et al. (2019) directly investigated the impact of running between the wickets to extensors (quadriceps femoris) and flexors (biceps femoris) of the knee from isokinetic dynamometry. Specialist, sub-elite batters displayed reduced peak torque in knee flexion for both concentric and eccentric contractions following an intervention lasting seven overs. Which also translated to reduced running performance i.e., increased sprint times over the 17.68m distance (Christie et al. 2019). Again, the rate of run scoring was posited to be a moderator of muscular damage and fatigue. A high-volume running intervention, mimicking increased run scoring rates, caused an 18% reduction to peak torque in flexors of the knee (Christie et al. 2019). While the moderate-volume intervention, although matched for duration, caused no significant reduction in peak torque of knee flexors (Christie et al. 2019).

Christie et al. (2019) determined run scoring rates and running volume from time-motion analyses of ODI's, excluding PowerPlay overs. The high-volume intervention instructed batters to run two shuttles every delivery (2 runs x 42 repetitions) and the moderate-volume intervention imposed two shuttles every second delivery (2 runs x 21 repetitions) (Christie et al. 2019). A critique can be made against this method as an individual innings organically entails a less cadenced running structure. Match dynamics such as PowerPlays/fielding changes, bowling changes, dismissal of batters – imply that boundaries and running volume, are not uniformly distributed throughout an innings. Relatedly, Petersen et al. (2010) reported that one hour of batting in ODI's produces a similar overall distance coverage as a Twenty20 innings (2476 ± 720 vs $2429 \pm 657m \cdot h^{-1}$). But more distance is covered sprinting per hour in a Twenty20 innings (458 ± 202 vs $389 \pm 201m \cdot h^{-1}$) (Petersen et al. 2010; Petersen et al. 2011). Therefore, to fully elucidate the impact of run scoring rate on muscular function and other physiological parameters, replicating the undulations of a competitive match is necessary (Menzel et al. 2013; Morin et al. 2015; Morel et al. 2015).

Muscular consequences of run scoring are also of interest for injury-risk profiling and prevention. Shuttle running, an analogue of running between the wickets, is known to alter muscular function (Highton, Twist, and Eston [2009]) from asymmetric actions of eccentric contractions from knee flexors and concentric contractions from knee extensors (Coombs and Garbutt [2002]). Hamstring:Quadriceps (H:Q) ratios are therefore used to quantify concentric and eccentric strength at the knee to highlight asymmetry (Aagaard et al. [1998]; Coombs and Garbutt [2002]). A balanced concentric ratio (Hcon:Qcon) of 1:1 indicates that equal force is produced in concentric contractions flexion and extension (Aagaard et al. [1998]; McGuigan et al. [2006]). Joint stability is calculated from the ratio of eccentric flexor and concentric extensor (Hecc:Qcon) strength, and unbalanced strength profiles are associated with an increased injury risk (Coombs and Garbutt [2002]; McGuigan et al. [2006]). How a prolonged batting innings affects these strength profiles is of interest to research and sport practitioners developing strength and conditioning programs for batters. Christie et al. ([2019]) reported that joint instability is exacerbated by increased running volumes and decelerative efforts. Therefore, batting at high run scoring rates should be further examined to develop an understanding of conditioning requirements and recovery strategies. Where isokinetic dynamometers are logistically unavailable, similar strength profile analysis can be determined from the Eccentric Utilisation Ratio (EUR) of vertical jump performance.

Lower-limb PPO can be extrapolated from maximal vertical jump height, flight time, or directly measured from force plates/mats (Markovic et al. [2004]). The assessment begins standing upright, then into 90° of flexion at the hip and knee and forcefully into full extension for a maximal vertical jump (Markovic et al. [2004]). Muscular function of the stretch-shortening cycle (SSC) is then assessed from two distinct methods of initiating the jump (Gheller et al. [2023]). In the Counter Movement Jump (CMJ), athletes are permitted to eccentrically load lower-limb musculature by rapidly descending, then immediately initiating the jump once 90° of hip and knee flexion is reached (Markovic et al. [2004]; Gheller et al. [2023]). The rapid descent merged into the concentric contraction of extension enables passive tension stored in the eccentric (descending) phase to contribute to force production of the jump (Markovic et al. [2004]; Gheller et al. [2023]).

In contrast, the Squat Jump (SJ) requires the athlete to pause (for a count of three-five seconds) at 90° of hip and knee flexion (Markovic et al. [2004]). The rationale for maintaining the flexed, active position, is to diminish muscular tension stored from the SSC and therefore, force output is restricted to concentric production (Markovic et al. [2004]; Gheller et al. [2023]). A ratio of eccentric: concentric (EUR = CMJ/SJ) describes the contribution of the SSC to power output, and performance changes associated with

fatigue can be related to muscular functioning (McGuigan et al. 2006). Increased CMJ performance, relative to SJ, reveals that muscular integrity of storing potential energy is intact (McGuigan et al. 2006; Gheller et al. 2023).

The repeated eccentric contractions of run scoring are hypothesised to impact muscular functioning, reducing the batters' EUR, suggesting potential for injury due to joint instability (Christie et al. 2019). Interestingly, Houghton and Dawson (2012) reported an increased EUR in skilled batters following a 30-over batting intervention. Although sprint performance diminished as the simulated innings progressed, CMJ height was unaffected while SJ performance was impaired (Houghton, Dawson, and Rubenson 2011; Houghton and Dawson 2012). It is conceivable that skilled, experienced batters develop specific strength adaptations to counteract the extreme eccentric demands of batting (Noakes and Durandt 2000). Delayed assessments however, revealed that muscular functioning was impaired 24-hours post-batting with both CMJ ($d = 1.38$) and SJ ($d = 0.80$) performance significantly impaired (Houghton and Dawson 2012). Ultimately, exercise-induced muscular damage and the actions of run scoring impart measurable deficits to lower-limb muscular functioning (Scanlan et al. 2016; Christie et al. 2019) and further study is warranted for varying batting intensities.

Upper-body muscular control and strength should also be considered. A cricket bat has an asymmetrical mass distribution (Curtis, Heller, and Senior 2021) and small area on the face of the bat ('sweet region') where post-impact ball speeds are maximised (Peploe et al. 2018). Few studies have investigated the actions of stroke play, which like running between the wickets, can be dissected into phases. The 'back lift' entails how the batter raises the height of mass (forearms, hands and bat) directly involved in the kinematic forces of the bat swing (Peploe et al. 2019; Noorbhai 2020a). Noorbhai (2020a) describes two distinct techniques where the endpoint of the back lift aligns the toe of the bat near and parallel to the frontal plane of the batter (straight back lift). Or the bat moves away from the batter and creates a lateral angle with the frontal plane (lateral back lift) (Noorbhai and Noakes 2016; Noorbhai 2020a). Both techniques aim to raise the center of mass of the bat through flexion at the wrist and elbow (Peploe et al. 2019). With horizontal shoulder abduction (lead shoulder) and adduction (Peploe et al. 2019).

Ultimately, the back lift increases the potential energy stored in the system of bat and batter (Peploe et al. 2019; Noorbhai 2020a). The 'downswing' or 'follow-through', begins from a raised height where stored potential energy can be transferred into kinetic energy to the blade of the bat Noorbhai 2020a. The batter extends at the wrists and elbows, elongating the moment-arm from shoulder-wrist to generate bat speed (Peploe

et al. [2019]. The determinants of bat speed have been identified as increased extension of the lead elbow and increased wrist unlocking (flexion to extension) (Peploe et al. [2019]). Further, potential energy is thought to be stored in the SSC of musculature in the thorax (Peploe et al. [2019]). Increased degrees of thoracic and pelvic separation in the transverse plane allow the downswing to include rotational force of the thorax, stretched during the back lift, and returning to transverse alignment of the pelvis throughout the downswing (Peploe et al. [2019]). Upper-body strength, measured by a 1-rep maximum on the bench press, has also been positively correlated with post-impact ball carry distance (Taliep, Prim, and Gray [2010]). While Nunes and Coetzee ([2007]) named increased peak torque of internal shoulder rotation to be a predictive trait of successful batters.

1.1.2 Metabolic costs of run scoring

This far, it is evident that the actions of batting recruit large volumes of upper and lower-body musculature. Sustained muscular contractions impose an energetic (ATP) demand, which in humans, is metabolised from substrates via mitochondrial oxidation or cellular anaerobic glycolysis (Brooks [2011]). Therefore, the oxidative and anaerobic stress of Twenty20 batting should be compared with the intermittent, high-intensity activity profile described in previous studies and other formats (Petersen et al. [2011]; Vickery et al. [2018]).

Variables of anaerobic metabolism

High-intensity physical activity requires ATP-yielding metabolism to be expedited to meet the demands of frequent and forceful muscular contractions (Barclay [2011]). Anaerobic metabolism of glucose generates ATP rapidly but, with sacrificed biochemical efficiency (Brooks [2011]; Barclay [2023]). Contracting skeletal muscles increase the expression of GLUT4 (glucose type 4 transporter) channels, enabling increased diffusion of glucose into cytoplasmic space (Richter and Hargreaves [2013]; Bradley et al. [2015]). The microenvironment of muscular cytoplasm then determines the metabolic fate of glucose (Brooks [2011]; Evans et al. [2019]). And when ATP supply is challenged, exceed yielding capacity of oxidative phosphorylation, the product of glycolysis (pyruvate) undergoes lactic acid fermentation to anaerobically yield 2 additional ATP molecules (Brooks [2011]; Barclay [2023]). Ultimately, anaerobic glycolysis supplies ATP up to 100-times faster than oxidative alternatives but, depletes substrate stores of glucose and glycogen at increased rates (Barclay [2011]; Evans et al. [2019]). Further, hydrogen ions [H^+] produced from the transport and clearance of lactate from cytoplasmic to

interstitial space, decreases cellular pH, potentially interfering with subsequent enzyme activity and metabolism (Van Hall [2010](#); Brooks [2020](#)). The muscular workload where ATP demand increases the production of lactate in driver cells, therefore, describes a metabolic compensation or fulcrum termed the lactate threshold (Brooks [2020](#)).

Blood lactate concentrations define the physical workloads which exceed aerobic tolerance (Evans et al. [2019](#); Brooks [2020](#)). At the lactate threshold, the rate of lactate production inhibits oxidative pathways, indicating that the experienced muscular output is anaerobically dominated (Evans et al. [2019](#); Brooks [2020](#)). Hence, the rate of substrate utilisation is increased, and the exerciser's capacity to maintain the current muscular output is increasingly finite (Evans et al. [2019](#)). A second workload limit is defined at the concentration of $4\text{mmol} \cdot \text{L}^{-1}$, where the Onset of Blood-Lactate Accumulation (OBLA) begins to increase exponentially corresponding with severe intensities (Beneke, Leithäuser, and Ochental [2011](#)). The metabolic consequences of accelerated lactate production include the depletion of high-energy phosphates and therefore ongoing muscular output may be compromised to varying degrees (Van Hall [2010](#); Brooks [2011](#)). Thus, quantifying lactate metabolism supplies considerable insight to the muscular workloads and metabolic adaptations needed to sustain batting performance in a prolonged innings.

Twenty20 cricket has received little attention in this regard to date. To our knowledge, no study has reported blood lactate concentrations of batters during or after competitive match play in any match format. The physiological responses of batters to a simulated innings with similar movement demands to an ODI's, produced blood lactate concentrations which ranged from $3.0 - 5.0\text{mmol} \cdot \text{L}^{-1}$ (Houghton, Dawson, and Rubenson [2011](#)). In small-sided cricket games contested on smaller fields, Vickery, Dascombe, and Duffield ([2014](#)) reported lower concentrations of $1.1 - 2.0\text{mmol} \cdot \text{L}^{-1}$. Finally, Petersen et al. ([2011](#)) investigated the conditioning sessions of elite batters and reported peak lactate concentrations of $4.7 - 9.7\text{mmol} \cdot \text{L}^{-1}$ – concluding that training was designed to exceed the expected demands of match play for enhanced adaptations (Petersen et al. [2011](#)). Given the sparsity of batting related data overall, further study particularly surrounding Twenty20 cricket is necessary. When considering the method of obtaining blood lactate observations, the timing of assessments should also be considered. The 30-over ODI innings simulation, and measurements reported by Houghton, Dawson, and Rubenson ([2011](#)) were obtained every 10 overs. Hence, mini periods of highest intensity may be unreported and particularly, the carry over of findings to the 20-over format may be limited. Continuous measurements like heart rate and oxygen consumption can therefore supplement lactate measurements

where a respite in activity/batting is necessary to obtain samples.

Cardiovascular and aerobic variables

The aerobic demands of batting have received marginally more research attention. Prolonged physical activity requires energy metabolism which supplies high ATP-yield from finite substrate stores (Hoppeler et al. [2003]; Brooks [2011]). Inspired oxygen (VO_2), transported to mitochondria in muscle tissue, acts as the terminal proton acceptor in the electron transport chain, where the process of oxidative phosphorylation yields up to 18 times more ATP than anaerobic metabolism (Brooks [2011]; Radak et al. [2013]). Further, Acetyl-CoA entering the tricyclic acid cycle, generating electron carriers ($NADH + FADH_2$) for the electron transport chain, can be derived from multiple sources, including fatty acids (Brooks [2011]). Aerobic metabolism is therefore, most biochemically efficient in ATP-yield per unit of substrate (Radak et al. [2013]). And benefits from using substantially larger substrate banks – adipose tissue and glycogen stores (Brooks [2011]). Thus, oxygen consumption is a primary variable when describing the metabolic workload and intensity characteristics of exercise. While peak oxygen consumption per unit of time is indicative of maximal aerobic capacity and metabolic adaptations to stress (fitness) which can be directly compared across various sports.

The maximum aerobic capacity (VO_{2max}) of elite batters, estimated from a 20m shuttle running test, has been reported by Johnstone and Ford ([2010]). Batters displayed marginally greater aerobic capacity ($56.1 \pm 4.5 ml \cdot min^{-1} \cdot kg^{-1}$) than bowlers ($54.1 \pm 2.8 ml \cdot min^{-1} \cdot kg^{-1}$). But in contrast to earlier hypotheses, produced less upper-body strength in a vertical medicine ball throw ($7.0 \pm 0.1 m$ vs $7.7 \pm 0.6 m$) (Johnstone and Ford [2010]). Elite batters expectedly possess superior aerobic capacities than the general population (Wilson and Tanaka [2000]) and are comparable with elite rugby union and baseball players (Noakes and Durandt [2000]; Johnstone and Ford [2010]).

During batting, a short 7-over bout produced a mean oxygen consumption of $26.9 ml \cdot min^{-1} \cdot kg^{-1}$ in experienced batters (Pote and Christie [2014]). While prolonged batting for 30-overs resulted in a mean consumption ranging from $29.3 \pm 6.1 - 43.4 \pm 6.3 ml \cdot min^{-1} \cdot kg^{-1}$ (Pote and Christie [2016a]). Thus, further hypotheses are raised about the duration and intensity of a batting bout/innings on the physiological responses of batters. The overall energy expenditure of an innings is likely increased as a function of duration but, the effect of run scoring intensity is less clear. To accurately assess oxygen consumption during batting, however, gaseous exchange at the mouth is measured continuously. And the measurement apparatus is worn by the athlete which may interfere with batting or inflate results. Heart rate can be measured less intrusively

than oxygen consumption, but, provides a strong correlate of oxygen consumption (Pettitt et al. [2007]; Reis, Tillaar, and Marques [2011]) and overall cardiopulmonary stress.

Heart rate responses have been reported across several batting scenarios with some variability. In competitive match play, Twenty20 batting produced the highest mean heart rates of $149 \pm 17 \text{ beats} \cdot \text{min}^{-1}$ compared to $144 \pm 13 \text{ beats} \cdot \text{min}^{-1}$ in ODI's (Petersen et al. [2010]). In short 7-over batting bouts, mean heart rates of skilled batters ranged from $145 - 166 \text{ beats} \cdot \text{min}^{-1}$ (Pote and Christie [2014]). Similar to the mean of $164 \pm 12 \text{ beats} \cdot \text{min}^{-1}$ reported by Vickery, Dascombe, and Duffield ([2014]) in the small-sided game scenario. Finally, the 30-over ODI innings simulation produced ranges of $124 \pm 15 - 159 \pm 14 \text{ beats} \cdot \text{min}^{-1}$ (Pote and Christie [2016a]) and $114 \pm 8 - 147 \pm 15 \text{ beats} \cdot \text{min}^{-1}$ (Houghton, Dawson, and Rubenson [2011]). These studies further demonstrate the intermittent activity profile of batting. Where periods of lower intensity and cardiovascular strain, allow aerobic recovery for periods of high intensity, where anaerobic power is essential. To date no study has reported Excess Post-Exercise Oxygen Consumption (EPOC) characteristics of batting, which may provide greater insight to energetic variances between innings and game formats.

1.1.3 Environmental factors of batting stress

Like many sports, cricket games are contested in an outdoor environment where athletes are exposed to the elements. Dehydration and heat stress can adversely affect batters uniquely, due to the thermal properties of protective gear (Gore et al. [1993]; King, Christie, and Todd [2002]). The movement demands and physical strain discussed above are more substantial considering that batters are performing while wearing a helmet, gloves and leg padding covering upper thigh to ankle. Beyond the demands of carrying extra mass, which likely detracts running performance (Loock et al. [2006]) although not yet fully studied.

The impact of protective gear on heat stress and fluid loss, may increase the physical strain of batting. Gore et al. ([1993]) first reported similar heart rates if batters performed in a cool ($22.6 \pm 0.7^\circ\text{C}$) or warm ($32.9 \pm 0.3^\circ\text{C}$) environment. Sweat rates, however, were increased in warm conditions, with batters losing $0.7 \pm 0.03 \text{ L} \cdot \text{h}^{-1}$ (Gore et al. [1993]). Similar rates of fluid loss per hour ($0.9 \pm 0.2 \text{ L} \cdot \text{h}^{-1}$) were observed by Houghton, Dawson, and Rubenson ([2011]) and although batters were permitted $4 \text{ ml} \cdot \text{kg}^{-1}$ of carbohydrate solution during the 2-hour batting protocol, an overall mass loss of $0.7 \pm 0.5 \text{ kg}$ was reported (Houghton, Dawson, and Rubenson [2011]). Further, the thermal effect of padding (compared to batting with no protective gear) has been shown

to increase skin temperature of the forehead ($36.8 \pm 0.6^\circ\text{C}$ vs $35.4 \pm 1.1^\circ\text{C}$) (King, Christie, and Todd [2002]). Which corresponded to an increased sweat rate ($1.05 \pm 0.2 L \cdot h^{-1}$ vs $0.90 \pm 0.2 L \cdot h^{-1}$) (King, Christie, and Todd [2002]).

Increased metabolic activity and resultant thermogenesis of exercise, shifts thermal homeostasis to increase heat loss mechanisms, particularly evaporative heat loss through the excretion of sweat (Flouris and Schlader [2015]). Thus, sodium gradients in eccrine glands promote the excretion of fluid, and consequently electrolytes (Na^+), from blood plasma to upper epidermal layers to promote evaporative heat loss (Maughan [2013]; Flouris and Schlader [2015]). Prolonged exercise and increased sweat excretion, therefore, result in a reduction of blood volume i.e., dehydration (Maughan [2013]). Which compromises mean arterial blood pressure and the adequate perfusion of skeletal muscle tissue, potentially contributing to reduced performance and fatigue (Maughan [2013]; Gamage et al. [2016]). Gamage et al. ([2016]) identified that if mass (fluid) loss is restricted to less than 1%, no statistical difference in performance is measured when running between the wickets. However, reduced body mass of greater than 3.7% and moderate dehydration resulted in impaired performance running between the wickets and accuracy in fielding drills (Gamage et al. [2016]). Therefore, the effect of prolonged batting while wearing protective gear should be further studied in various environmental conditions and workloads.

1.1.4 Fatigue

The underlying mechanistic basis of fatigue is multifaceted and debated. For the purpose of this review, the definition of fatigue relates to the inability to maintain a preceding state/level of performance due to repetition or insufficient rest from intense workloads (Ament and Verkerke [2009]). Several systems may lose homeostatic balance during exhaustive exercise and therefore, multiple causal relationships for diminished functioning/performance are hypothesised. Hence, determinants of fatigue are broadly categorised into peripheral or central mechanisms (Gandevia [2001]; Ament and Verkerke [2009]).

Peripheral fatigue mechanisms implicate deficiencies at the cardiovascular and muscular level (Ament and Verkerke [2009]). Cardiovascular and energy supply/depletion models posit that performance is determined by the exerciser's capacity to generate ATP (Allen, Lamb, and Westerblad [2008]; Ament and Verkerke [2009]). As such, the supply of substrate and oxygen, interlinks with the generation and removal of waste metabolites (Allen, Lamb, and Westerblad [2008]). Therefore, cardiovascular insufficiency is considered the underlying performance bottleneck (Abbiss and Laursen [2005]). Other

peripheral models contend that performance is diminished instead, due to alterations in muscle structure and function (Allen, Lamb, and Westerblad [2008]; Highton, Twist, and Eston [2009]; Debold, Beck, and Warshaw [2008]). The role of hydrogen ions and pH in muscle tissue, originating from metabolites of anaerobic glycolysis, are now believed to be overestimated and outweighed by power-yielding the benefits of lactate production (Allen, Lamb, and Westerblad [2008]; Hall et al. [2016]; Brooks [2020]). However, evidence in single myosin units demonstrate that increased concentrations of hydrogen and phosphate ions impede the motion of contractile units (Debold, Beck, and Warshaw [2008]). Another possible mechanism involves diminished reuptake and release of Calcium ions (Ca^{2+}) from the sarcoplasmic reticulum, caused by increased concentrations of adenosine diphosphate (ADP) and reactive oxygen species (Moopanar and Allen [2005]; Keyser [2010]). Or, decreased sensitivity of contractile proteins to Ca^{2+} (Gorga, Fishbaugher, and VanBuren [2003]). Crystal structure analysis implicates that troponin remains bound to actin filaments in the absence Ca^{2+} , preventing contractile units from interacting and binding (Takeda et al. [2003]). Ultimately resulting in reduced tropo-myosin binding and therefore force production (Debold [2012]).

Central fatigue mechanisms on the other hand, implicate paraspinal and spinal deficits leading up to the neuromuscular junction (Gandevia [2001]; Ament and Verkerke [2009]). Impaired neural drive and neurotransmitter cycling may reduce action-potential amplitude at the neuromuscular junction (Gandevia [2001]). Thus, excitation of the sarcoplasmic reticulum is hindered (Fuglevand [1995]; Gandevia [2001]). The rate of motor unit recruitment (rate coding) is also believed to decrease, negatively effecting force development (Jensen, Pilegaard, and Sjøgaard [2000]; Enoka and Duchateau [2017]). A prominent theory, termed the Central Governor Model, posits that a paraspinal modulation precedes the observed spinal and peripheral deficits (Noakes, Peltonen, and Rusko [2001]; Noakes [2012]). It is argued that a central mediator in the brain acts to primarily protect cardiac tissue from ischemia, without which catastrophic failure would be imminent (Noakes, Peltonen, and Rusko [2001]; Noakes [2012]).

A 'Central Governor' therefore, dictates the efferent output which reaches neuromuscular junctions. And actively dampens the recruitment of muscle mass to remain below the energetic limits of maximal cardiac output (Noakes, Peltonen, and Rusko [2001]; Noakes [2012]). The inputs and mechanisms of this efferent control are not fully understood. Noakes, Peltonen, and Rusko ([2001]) initially hypothesised that the ongoing computational costs of coordinating movement and muscular recruitment would alter neurotransmitter concentrations within the brain. Which then initiates self-regulatory, preservative mechanisms of dampening neural impulses (Noakes, Peltonen, and Rusko

[2001]. Abbiss and Laursen ([2005]) later suggested that core body temperature may be a key variable monitored by the hypothalamus to prevent excessive heat production by controlling neural drive and sympathetic output. More recently, the role of conscious perception of effort has been implicated.

The anticipatory feedback model expands on central governor theory. It is argued that conscious effort regulation is a key object of achieved output/performance (Tucker and Noakes [2009a]). That is, performance is moderated based on the anticipation of required effort and current physiological feedback of perceived exertion (Tucker and Noakes [2009a]; Tucker and Noakes [2009b]). Measured variables of fatigue, therefore, are the result of volitional performance reduction or termination of exercise, to ensure output does not exceed the physiological capacity of the exerciser (Tucker and Noakes [2009a]; Tucker and Noakes [2009b]).

In the sporting context, authors argue that an athletes previous experiences create a ‘template’ of expected states of exertion (Pageaux [2014]; Smits, Pepping, and Hettinga [2014]). Hence, at the onset of a marathon, a runner has a conscious expected state of exertion for the initial periods of activity, through to the finishing efforts required, and performance is continually monitored within this template (Tucker and Noakes [2009a]; Pageaux [2014]; Smits, Pepping, and Hettinga [2014]). Importantly, the model also proposes how the athletes experience is used to adequately distribute finite energy and effort stores throughout an activity for optimal performance (Smits, Pepping, and Hettinga [2014]). Based on the template of previous efforts, performance is regulated from current physiological feedback and the anticipation of latter efforts and hence current output may be dampened for latter gains in performance (Tucker and Noakes [2009a]; Pageaux [2014]; Smits, Pepping, and Hettinga [2014]). Experienced batters may therefore moderate physical outputs throughout an innings to maintain an expected state of exertion which is conducive to batting performance, as demonstrated by Christie et al. ([2018]). Such moderation of physical performance would require computation of physiological feedback and anticipation/forecasting of upcoming events which may increase the neural workload/intensity of an innings.

1.2 Neural Components of Batting – The Mind of a Batter

1.2.1 Neuroanatomy of Perception-Action Coupling

Batting is an interceptive motor-task, demanding astute decision-making, coordination, and temporal accuracy of movement (Sarpeshkar and Mann [2011]; Scanlan et al. [2016]). To strike a high-velocity cricket ball, visual stimuli is integrated with movement

of several antagonistic muscles (Sarpeshkar and Mann [2011](#)). Thus, a large volume of neural matter must be recruited. First, the recognition and transmission of visual stimuli involves multiple neural structures. Impulses originating from phototransduction in the retina, travel via the optic nerve to the optic chiasm anteriorly of the pituitary gland (Schiefer and Hart [2007](#)). Stimuli from peripheral vision of each eye crosses into the alternate cerebral hemisphere before reaching the primary visual cortex (V1) of the occipital lobe and lateral geniculate nucleus in the thalamus (Schiefer and Hart [2007](#)). The primary visual cortex relays stimuli to relevant substructures V2-V5. Which in the cricketing context, largely involves the detection and analysis of motion, therefore, interaction between V1 and V5 (Middle Temporal Area) is key (De Moraes [2013](#)). Finally, the dorsal stream interacts with V5 and the Medial Superior Temporal Area (MSTA) to integrate the global flow of visual stimuli, enabling the perception of spatial location and relative motion (De Moraes [2013](#)) which can then guide motor actions (Hutchison and Gallivan [2018](#)).

Voluntary motor actions, in this case the responding ‘stroke’, ‘drive’, ‘pull’, ‘hook’ etc. involve the contraction and antagonistic inhibition of several muscle bodies, recruiting various cerebral structures. Primarily the motor and pre-motor cortex, located in the frontal lobe, initiate the neuronal signature of a specific, planned motor behaviour (Shadmehr and Krakauer [2008](#)). Before impulses reach neuromuscular junctions, fine-tuning of coarse neural signatures must be applied, and continually re-adjusted from sensory feedback during movement (Shadmehr and Krakauer [2008](#)). Structures of the Basal Ganglia, the Subthalamic Nucleus and Substantia Nigra, ventral of the thalamus, provide oversight of impulses for improved motor control (Groenewegen et al. [2003](#)). While the brunt computation of differentiating impulses to specific motor neurons is processed by the cerebellum (Groenewegen et al. [2003](#); Shadmehr and Krakauer [2008](#)). With additional sensory feedback for error-monitoring, enabling the coordination of movements with very high precision (Shadmehr and Krakauer [2008](#)). Plainly, complex, multi-joint motor behaviours are preceded and continually monitored through intense computation (Shadmehr and Krakauer [2008](#)). The selection of a specific stroke, however, requires perception of visual stimuli. In other words, integrative processing lies between the transmission of visual stimuli and the initiation of a motor response (Fuster [2017](#)). Perception-action coupling in batting can therefore be considered analogous of the interaction between software and hardware.

Cortical structures involved in the transduction of visual stimuli, and structures responsible for neural outputs that produce muscular contractions can be considered

hardware. Whereas underlying mental processes, or *software*, are responsible for assimilating nuanced stimuli characteristics with planned actions, providing instruction for hardware to attain specific goals (Fuster [2017]; Hutchison and Gallivan [2018]). Both distinctions are substantial neuroscience topics. The neural hardware of transduction and motor output alone, requires more extensive review beyond the scope of this thesis. Therefore, the purpose of this review and investigation, surrounds the integrative mental processes (cognition) of goal-directed behaviour. That is, how perceived information from the environment is integrated with internal cognitive representations to plan and execute motor actions (Rolfs and Schweitzer [2022]). Such integrative processing is enabled by the neuronal layering of the prefrontal cortex (PFC) (Fuster [2013]). Specifically, synaptic input from multiple cerebral structures is collated via the external and internal granular layers to be perceived for decision-making (Fuster [2001]; Fuster [2013]). Thereafter, projecting neurons of the external and internal pyramidal layers innervate cerebral structures involved in motor initiation and control (Fuster [2017]; Rolfs and Schweitzer [2022]). Finally, the molecular and multiform layers enable flow of information within the PFC, enabling extensive synaptic communication for higher-order processing (Fuster [2017]).

1.2.2 Information Processing in Batting Behaviour

The cognitive components of batting are not well studied. Skilled batters, however, have been shown to possess superior cognitive abilities to their lesser-skilled counterparts (Weissensteiner et al. [2008]). Particularly in the ability to predict characteristics of an upcoming delivery, such as the location of bounce, trajectory, and flight path. Rather than relying on visual stimuli of ball-flight alone, skilled batters increase the sample of processed stimuli by reading kinematic variables in the bowling action before ball-release. (Weissensteiner et al. [2008]; Mann, Spratford, and Abernethy [2013]). This anticipation may allow skilled batters to intercept successive deliveries with higher accuracy into gaps in the field (Abernethy and Zawi [2007]; Portus et al. [2010]) and nullifies the bowlers attempts to deceive through ‘swing’ and ‘seam’ variations which cause late deviations in trajectory (Müller, Brenton, and Mansingh [2021]; Müller, Brenton, and O’Grady [2023]). Thus, how batters distinguish information to process/reject, is key to overcoming the extreme temporal constraints of intercepting a delivery.

Batting strokes are examples of learned perception-action couples (Hutchison and Gallivan [2018]). During skill development and practice, batters learn to associate movements which correspond to specific stimuli. For example, a delivery which is bouncing near the batter (‘full-length’) typically requires a forward step/lunge toward the location

of bounce for a controlled drive (Jamil et al. [2022](#)). In learning and practice, batters associate the visual stimuli of full-length deliveries with relevant motor actions, like playing a drive (Shadmehr and Krakauer [2008](#); Hutchison and Gallivan [2018](#)). Long-term memories of these perception-action couples can then be formed in the associative parietal cortex, which interacts with the primary motor cortex, allowing familiar stimuli to be responded to with minimal latency (Poljac, Schie, and Bekkering [2009](#); Fuster [2017](#)). Physical limitations (i.e., visual-motor delay) must be present in the hardware of stimulus encoding and motor action (Sarpeshkar and Mann [2011](#)). Thus, motor actions must be coordinated based on predictions of where a delivery will be (Sarpeshkar and Mann [2011](#)). In other words, responding strokes cannot be not rigid, pre-planned motor actions. But rather the result of prospective motor control (Sarpeshkar and Mann [2011](#)), where initiated perception-action couples are altered ‘online’ as further relevant stimuli are availed (Poljac, Schie, and Bekkering [2009](#); Fuster [2017](#)).

Anticipating delivery characteristics requires acute processing of specific kinematic cues in the bowlers’ shoulder, arm, and hand (Müller, Brenton, and Mansingh [2021](#)), allowing appropriate perception-action couples to be initiated sooner. There is further evidence that batters will use contextual information (fielding positions and other tactical cues) to aid in anticipating upcoming deliveries with their corresponding in/appropriate strokes (Müller, Brenton, and O’Grady [2023](#)). Therefore, among the arsenal of learned perception-action couples, batters must also possess a mechanism of filtering responses to favour or inhibit. From mental processes that begin in advance of ball-release, and to account for visual-motor delay, must be confirmed prior to contact (Sarpeshkar and Mann [2011](#)).

According to dual-processing theory, humans and batters use two distinct mechanisms to compute responses to information (Evans and Stanovich [2013](#); Furley, Schweizer, and Bertrams [2015](#)). Implicit processing, which is described by autonomous responses that are triggered by current context or stimuli (Evans and Stanovich [2013](#); Thompson [2013](#)). Learned perception-action couples, for example, are autonomously initiated and can be run to completion through implicit processing of availing stimuli (Thompson [2013](#); Furley, Schweizer, and Bertrams [2015](#)). The availing information already has a learned solution, providing a cognitive representation that can be reapplied without central executive (conscious) oversight (Evans and Stanovich [2013](#); Thompson [2013](#)). Thus, in tasks with high temporal constraints, implicit processing is upregulated to favour processing speed for response generation (Furley, Schweizer, and Bertrams [2015](#)).

Explicit information processing is engaged when novel responses to stimuli must be generated (Evans and Stanovich [2013](#); Thompson [2013](#)). Or, to inhibit and alter learned

cognitive representations (Keren and Schul [2009](#); Evans and Stanovich [2013](#)). Another view, is the dual-interventionist model, which describes that implicit processing is always initiated first and when not run to completion/solution - explicit processing intervenes (Evans and Stanovich [2013](#); Furley, Schweizer, and Bertrams [2015](#)). A short-term, malleable, memory store (working memory) holds goal-relevant information and is strictly monitored by a central executive for oversight of processing (Baddeley [1992](#); Baddeley [2012](#)). Explicit processing relies on working memory and central executive oversight, to integrate short-term ideas/concepts with long-term memories for high-order cognitive processes (Baddeley [2012](#); Evans and Stanovich [2013](#)). Although it is generally accepted that explicit processing is not temporally efficient and therefore inhibited when strict temporal constraints are presented (Furley, Schweizer, and Bertrams [2015](#)). Perception-action couples can be influenced/alterd by the contents of working memory, providing a filtering mechanism for motor responses (Poljac, Schie, and Bekkering [2009](#); Theeuwes [2010](#)). Put simply, from-ball-release and during motor action, stimuli must be implicitly processed and responded to with no excess latency (Furley, Schweizer, and Bertrams [2015](#)). Prior to ball-release however, explicit processing of contextual stimuli and other match dynamics can aid in priming a subset of perception-action couples for enhanced batting performance.

1.2.3 A Case for Executive Functioning, Working Memory, and Attention

The PFC is the primary site responsible for executive functions (Fuster [2013](#); Fuster [2017](#)). These high-order functions enable goal-directed, problem-solving behaviours through organisation, planning and adaptive responses (Fuster [2013](#); Fuster [2017](#)). A prominent theory, proposed by Baddeley ([1992](#)) and later revisited ((Baddeley [2012](#))), describes the platform of conscious thought and executive functions from the interaction between a central executive and working memory. It is posited that ongoing cognitive tasks are held in a malleable, short-term memory store termed working memory. Baddeley ([2012](#)) further describes independent compartments for different modalities of stimuli. The visuospatial sketchpad, which retains visual and visuospatial stimuli (Baddeley [2012](#)). And the phonological loop, maintained through internal dialogue or subvocalisations, for verbal and auditory stimuli of language comprehension (Baddeley [2012](#); D'Esposito and Postle [2015](#)).

The dorsolateral PFC (DLPFC) is associated with the maintenance of information in working memory compartments (Barbey, Koenigs, and Grafman [2013](#); D'Esposito and Postle [2015](#)) and ventrolateral PFC (VLPFC) activity is linked with selecting and monitoring the contents of working memory (Rottschy et al. [2012](#); Funahashi [2017](#)).

Fundamentally, each working memory compartment has limited capacity, and two independent systems are argued due to the interference observed in dual-task paradigms (Baddeley [2012]). Cognitive tasks with two competing stimuli engaging the same compartment, result in interference and reduced performance (Klingberg [2000]). While no interference is observed in dual tasks where discrepant stimuli engage the phonological loop and visuospatial sketchpad (Oberauer and Kliegl [2004]; Baddeley [2012]). More recently, a third compartment termed the episodic buffer, has been conceptualised for the role of integrating working memory compartments to provide a single coherent cognitive representation (Baddeley, Allen, and Hitch [2017]). Overall, the contents of working memory must be relevant to the goal-directed behaviour, achieved through central executive oversight (Baddeley [2012]; Baddeley, Allen, and Hitch [2017]).

A key aspect of goal-directed cognition is to reject non-relevant information from entering the frame of consciousness and interfering with ongoing tasks (Corbetta and Shulman [2002]). Hence, attention, is a function of the central executive to filter wide-ranging synaptic input, ensuring goal-relevant information is processed and maintained in working memory (Corbetta and Shulman [2002]; Oberauer [2019]). Visual attention is the filtering mechanism a batter uses to hone in on visual stimuli of the oncoming bowler, while rejecting non-relevant distractions in the visual field (Alais, Morrone, and Burr [2006]; Theeuwes [2010]).

Attentional resources are finite and therefore must be allocated to increase the representation of stimuli that will be most pertinent to intercepting the delivery (Young and Stanton [2002]). Thus, selective visual attention (Desimone and Duncan [1995]) describes the integration of raw stimuli/sensory processing without influence of prior knowledge and expectation – “bottom-up” processing (Corbetta and Shulman [2002]; Theeuwes [2010]). With ‘top-down’ sensory processing, where high-order cognitive representations like expectations, preferences and behavioural goals are used to highlight sensory information (Corbetta and Shulman [2002]; Jonikaitis and Moore [2019]). The neural basis of this integration is the frontoparietal attention network (Ptak [2012]). The visual cortex preattentively decomposes stimuli of the bowling action and ball-flight into distinct features (Ptak [2012]) such as the relative shape and angle of the bowling arm, the intensity of movement in the bowler’s front/non-bowling arm (Müller, Brenton, and Mansingh [2021]). High-order ‘top-down’ signals are then converged with pre-attentive features in a prioritisation map of the visual field (Ptak [2012]). In other words, prioritisation of upcoming stimuli occurs consciously (‘top-down’) by reasoning expectations, behavioural goals and preferences (Corbetta and Shulman [2002]; Engle

[2018]). While features of stimuli are unconsciously processed, decomposed ('bottom-up') and presented in neural structures of the attention network where select features can be highlighted according to top-down signals (Corbetta and Shulman [2002]; Ptak [2012]). Thus, attentional mechanisms are guided towards sensory perception of stimuli/information resembling the contents of working memory (Corbetta and Shulman [2002]; Engle [2018]; Jonikaitis and Moore [2019]).

The gaze behaviour of batters provides further evidence of stimuli prioritisation and control. It has been repeatedly demonstrated that batters do not fixate their gaze on the ball throughout its flight path, especially when competing against fast bowlers (Land and McLeod [2000]; Croft, Button, and Dicks [2010]; Mann, Spratford, and Abernethy [2013]; Discombe [2020]). Instead, gaze is fixated on the initial 50–60% of ball-flight (Land and McLeod [2000]; Croft, Button, and Dicks [2010]), thereafter the eye saccades to the predicted location of bounce on the pitch, and finally to the predicted location of bat-ball contact (Mann, Spratford, and Abernethy [2013]; Discombe [2020]). When competing against spin bowlers, gaze is fixated on the ball for a larger percentage of total flight-time (88%), compared to fast-bowlers (Discombe [2020]). Further, during the bowlers' approach to the crease, gaze is fixated on the head and shoulder, then diverted to the bowling hand and ball at the point of ball release (Discombe [2020]). Hence, the kinematic information from the bowling action used to anticipate upcoming delivery characteristics (Weissensteiner et al. [2008]; Müller, Brenton, and Mansingh [2021]), must work in tandem with predictive control of ocular movements to successfully intercept deliveries. In other words, the information that a batter perceives from the bowling action must influence subsequent saccadic eye movements after ball-release.

The frontoparietal attention network instructs ocular motion to prioritise *select* visual stimuli in the bowling action and subsequent ball-flight (Ptak [2012]; Engle [2018]). But the prioritisation of visual stimuli is dependent on the batter's cognitive representation of the playing environment and visuospatial working memory (Corbetta and Shulman [2002]; Jonikaitis and Moore [2019]; Oberauer [2019]). Therefore, executive functions and working memory have several implications on batting performance.

Throughout an innings, the batter's ongoing perception of the playing environment influences the contents of working memory and which stimuli to attend to. When perceiving a fast bowler, learned behavioural goals, expectations and preferences (Ptak [2012]; Jonikaitis and Moore [2019]) result in a prioritisation map to heighten perception of salient kinematic cues in the bowling action and stimuli of early-ball flight. Left-handed fast bowlers, however, use a kinematic bowling action with more trunk rotation than their right-handed counterparts (Olivier et al. [2023]). Hence, the kinematic cues

in the bowling action will be unique, and the batter's visual field prioritisation map must adequately represent the locale of pertinent stimuli for a left-handed bowler. The batter's perception of a change of bowler, results in a revaluation of behavioural goals, expectations and preferences, and thus the contents of working memory are updated (Gazzaley and Nobre [2012](#); Oberauer [2019](#)).

Another example stimuli prioritisation can be drawn from the placement of fielders. The batter's visuospatial working memory of the field is a cognitive representation of where runs are available and how they can be scored i.e., which responding strokes are viable. When a fielder is moved, the risk of scoring runs through a given stroke or area in the field may increase or decrease. The batter's perception of a changed fielding position requires the risk to reward ratio of strokes to be re-evaluated and thus behavioural goals, expectations and the contents within visuospatial working memory are modified (Ptak [2012](#); Jonikaitis and Moore [2019](#)). Resultantly, the batter's attention will be guided to stimuli that align with this modulated cognitive representation (Gazzaley and Nobre [2012](#); Engle [2018](#); Oberauer [2019](#)). If the perceived risk of run scoring has reduced, attentional mechanisms will increase the representation of stimuli that correspond with learned perception-action couples that take advantage of the new field placement (Corbetta and Shulman [2002](#); Engle [2018](#)). Contrariwise, if the risk of a given stroke has increased unfavourably, the batter's behavioural goals will reflect learned perception-action couples which should be inhibited (Yarrow, Brown, and Krakauer [2009](#)).

The executive functions of strategising match stimuli, to update cognitive representations are therefore pertinent to sustained batting performance. How a batter perceives bowling changes, fielding changes, innings progression and other match dynamics directly impacts the representation of upcoming stimuli (Yarrow, Brown, and Krakauer [2009](#); Furley, Schweizer, and Bertrams [2015](#)). Thus, incorrectly, or partially evaluating the underlying context of a bowling and fielding change has conceivable detriments to stroke selection (decision making) and batting performance (Yarrow, Brown, and Krakauer [2009](#); Gray [2011](#)). The ability to update strategies, switch attentive sets and adapt to changing environments (or match context) is described by an executive function termed set shifting or cognitive flexibility (Stemme, Deco, and Busch [2007](#); Dajani and Uddin [2015](#)). To switch task sets and modify responses to stimuli, cognitive representations must be updated, preparing neural resources for enhanced efficiency (Stemme, Deco, and Busch [2007](#)).

The DLPFC and Anterior Cingulate Cortex (ACC) are recruited for error-monitoring and feedback, allowing actions and strategies, maintained in working memory, to be

adjusted based on evolving goals and environments (Baddeley [2012]; Dajani and Uddin [2015]). Similarly, when playing on a pitch of unknown hardness, the batter's preferences, expectations, and behavioural goals may need to be adjusted according to these environmental conditions (Rietbergen et al. [2018]). Preferred strokes may be inherently risky and therefore should be adjusted for risk-averse alternatives in the batter's cognitive representation of the task (Rietbergen et al. [2018]). Or, as innings progresses, the risk of being dismissed may be outweighed by the necessity to score runs and the batter should have the cognitive flexibility to update representations to reject prior risk-averse strategies (Dajani and Uddin [2015]; Furley, Schweizer, and Bertrams [2015]). Further, the behavioural goals maintained in working memory evolve as the innings and match progress (Engle [2018]). Batting in the first over of a match necessitates different cognitive representations to that of chasing a run target in the final overs of the second innings.

Viewed in this manner, a batting innings requires prolonged cognitive control. Where countless permutations of match context can be reasoned to set an optimal cognitive representation for anticipating deliveries and maximising batting performance (Furley, Schweizer, and Bertrams [2015]). But without wayward evaluations that result in poor cognitive representations of pertinent stimuli which subsequently will not be adequately attained to – inattentional blindness (Chun and Marois [2002]; Yarrow, Brown, and Krakauer [2009]). Therefore, it can be hypothesised that durable cognitive efficiency is a determinant of batting success in a prolonged innings.

1.3 Assessing Cognitive Function and Quantifying Acute Changes

In the clinical setting, parameters of cognitive functioning are measured to diagnose pathologies such as attention deficit disorder (Williams et al. [2010]), autism (Klinger and Renner [2000]), age related cognitive declines (amnesia, dementia (Freitas et al. [2012])) or brain trauma (Bechara et al. [1996]). Other research objectives monitor the impact of interventions (e.g drugs, sleep deprivation) for significant clinical outcomes or insight to ergonomics. Thus, several cognitive assessments have been developed to meet the requirements of different populations, settings and objectives (Poncet et al. [2017]). Considering the range of functions humans are capable of, assessments can be further categorised into the cognitive domains of interest. However, cognitive domains cannot be isolated entirely into separable components as functions are overlapping and exist rather on a scale of activation (Thompson [2013]). Hence, task paradigms

are developed to emphasise a parameter of cognition and typically quantify performance from independent variables such as error-counts, response times/speed, spatial accuracy, error-free streaks and other task-specific parameters. Table 1.1 summarises various cognitive domains of interest and assessments which have been developed to objectively quantify performance.

TABLE 1.1: Short description of select ‘pen and paper’ cognitive assessments

Cognitive Domain	Assessment	Description/Instruction
Executive Functioning, Attention, Inhibition, Cognitive Flexibility	Groton-Maze Learning Task (Pietrzak et al. 2008)	Navigate through a hidden maze in a 10x10 grid from top-left to bottom-right in fewest possible moves.
	Wisconsin Card Sorting Test (Bowden et al. 1998)	Match cards based on colour, shape, number without knowing the criteria of matching, but receive feedback on responses.
	Stroop Test (Siegrist 1997)	Name the colour of displayed text, which can be congruent or incongruent with the meaning of the word e.g., ‘blue’ in red text = incongruent.
	Flanker Task (Eriksen and Eriksen 1974)	Respond to a left (<) or right pointing (>) arrow which is in the centre of either congruent (e.g. <<<<<) or incongruent (<<><<) surrounding arrows.
	Stop Signal (Verbruggen and Logan 2008)	Respond as quickly as possible to a given stimulus (e.g., lowercase letter) but inhibit the accustomed response when a stop signal (e.g. uppercase letter) is presented

Table 1.1: Continued...

Cognitive Domain	Assessment	Description/Instruction
	Tower of London (Shallice 1982)	Rearrange three coloured beans, one move at a time, on three separate pegs to match the target arrangement in as few moves as possible, movements must be planned before starting
Memory, Working Memory	N-back (Jaeggi et al. 2010)	Is the card/symbol currently displayed identical to that in the previous cycle (1-back) or two cycles previously (2-back) ...
	One Card Learning (Falleti et al. 2006)	Recall (yes or no) if the displayed card has been seen before while cycling through a 52-card deck, novel cards introduced sporadically.
	Simon Task (Simon 1969)	Respond with left index finger to stimulus A and right index finger to stimulus B on separated buttons. Stimulus A/B randomly appear on the congruent half of the screen (e.g., A – left half) or incongruent half (A – right half)
Language	NAB Naming Test (Sachs, Rush, and Pedraza 2016)	Name the object in the displayed image.
	Semantic Fluency Test (Harrison et al., 2000)	Generate unique words in a category for 60 seconds in an array of categories
Processing Speed, Psychomotor function	Trail Making Test (Arnett and Labovitz 1995)	Connect a series of 25 dots as quickly as possible (Part A). Connect 25 dots quickly and accurately in numbered order (Part B)

Table 1.1: Continued...

Cognitive Domain	Assessment	Description/Instruction
	Response Time – Detection (Falleti et al. 2006)	One input/button to respond as quickly as possible to the appearance of a stimuli/symbol. Symbol appears at unpredictable intervals.
	Choice Response Time – Identification (Falleti et al. 2006)	Two inputs/buttons to respond as quickly as possible to the appearance of one of two corresponding, randomly appearing stimuli/symbols
Motor Skill	Grooved Pegboard Test (Ashendorf, Vanderslice-Barr, and McCaffrey 2009)	Dominant hand first, insert pegs into matching grooves in the pegboard, one peg at a time, without skipping slots or rows.
	Finger Tapping Test (Ashendorf, Vanderslice-Barr, and McCaffrey 2009)	Two fingers of the same hand on two buttons, tap buttons as fast a possible, alternating between fingers after each tap, for 20-seconds
Social Cognition	Reading the Mind in the Eyes (Baron-Cohen et al. 2001)	Select one of four possible descriptions for the emotive expression in a total of 36 images of eyes.
	Faux Pas Test (Baron-Cohen et al. 1999)	Recognise the portrayal of faux pas or poor social awareness in 10 scenarios/stories

Objectives for the design of cognitive assessments, as those listed in Table 1, are to be accessible for broad populations, meaning instructions are easily followed and performance is not hindered by the subjects' understanding of elaborate task requirements (Poncet et al. 2017). Second, the learning curve of performance should indicate stability after some acclimatisation to the task (Alexander, Paul, Michael, et al. 2003; Pietrzak et al. 2008), allowing the test-retest reliability (days, weeks, months between

assessments) to be investigated. Once re-test reliability is established, acute changes in cognitive function can be examined in accordance with clinical significance. For example, a hypothetical intervention study measuring the effect of an oral compound on psychomotor performance reveals a statistically significant increase in response times of 10 ± 5 milliseconds. The increased response time is then critiqued against the clinical significance of how detrimental or benign the observation could be for end-users. Experimental designs assessing cognitive function in the sporting context, however, benefit from sport-specific measures of performance.

To determine what effect an intervention would have on batting performance, measurements of cognitive and psychomotor performance should be representative of batting. Decisions during batting are derived from mental processes of a performer-environment interaction (Araujo, Davids, et al. 2009). Thus, batting behaviour is dependent on ecological cognition – the computation of environmental and internal stimuli exclusive to batting (Araujo, Davids, et al. 2009). Resultantly, to investigate the cognitive functioning of batters, task paradigms must sacrifice accessibility to broad populations. And rather specialise the task design to replicate parameters of ecological cognition of batting behaviour (Renshaw et al. 2019).

McMorris et al. (1999) and McMorris et al. (2006) demonstrated this rationale in the design of tasks that are specific to speed of information processing in soccer. Scaled models of a soccer field and players were photographed with model players placed in different attacking scenarios (McMorris et al. 1999; McMorris et al. 2006). The randomised photograph decks are presented to players who detect the presence of the ball to quantify the independent variables of speed and accuracy of visual search/processing speed. The task paradigm was developed in consultation with elite coaches, thus providing insight to the ‘clinical’ significance of performance and construct validity (McMorris et al. 1999; McMorris et al. 2006). Further, the authors note that elite players performing better than amateurs, who perform better than layman, indicates a task construct that examines an ecological parameter of soccer-specific cognition (McMorris et al. 1999). Therefore, results can be informative to sport-specific hypotheses with more carry over than less specialised task paradigms (Araujo, Davids, et al. 2009). Similar approaches to cognitive assessment have also been developed for volleyball (Castiello and Umiltà 1992), basketball (Furley, Memmert, and Heller 2010) and handball (Debanne and Fontayne 2009).

To date no studies have reported the development of a task paradigm to investigate ecological parameters of cognition in cricket. Resultantly, the few studies to report cognitive variables of batters were restricted to generalised task paradigms as listed in

Table 1 (Goble and Christie [2017]; Veness et al. [2017]). Considering the hypothesised role astute cognitive functioning will have on batting performance, it is important to increase the availability of cognitive variables associated with batting. Particularly with data that quantifies the efficiency of mental processes that are ecological to batting (Araújo, Davids, et al. [2009]; Renshaw et al. [2019]). Research should first elucidate cognitive components which are most influential to batting performance. For example, it can be reasoned that parameters of social cognition have little bearing on batting performance. But, executive functions, visual attention, psychomotor function, motor control among others have a conceivably large impact. Thus, deconstructing the performer-environment interaction of batters to identify mental processes that characterise executive functions allows batting-specific task paradigms to be reverse engineered (Duarte Araújo and Davids [2019]). Independent variables from these specialised task paradigms can be correlated with variables of batting performance to objectively assess construct validity (Renshaw et al. [2019]). And hypothesised cognitive determinants of batting performance can be further examined from ecological task paradigms that offer more transferable insights to coaching environments (Duarte Araújo and Davids [2019]).

1.4 Batting Through the Exercise-Cognition Interaction

The philosophy of mental acuity during physical stress dates to Charles Darwin, who wrote that “man cannot think deeply and exert his greatest muscular force”. Intuitively, the dispersal of effort for combined physical and mental outputs will result in some compromise of performance (Dietrich and Audiffren [2011]). Considering the physical workload and the fine cognitive requirements of an innings – peak batting performance appears delicately balanced. Exceedingly high physical strain may compromise cognitive efficiencies (Dietrich and Audiffren [2011]; McMorris [2016]), while the intense physical requirements of run scoring may be restrained due to demanding mental workloads (Zering et al. [2017]; Habay et al. [2021]). Although batting has received little attention, the mechanistic basis of the acute exercise-cognition interaction has been theorised predominantly from the modalities of running, cycling and rowing (Lambourne and Tomporowski [2010]). The relationship between the brain, physical stress and cognitive performance can first be conceptualised from the allocation of resources. Exercise increases the turnover of energy supply-demand in working muscles and neural matter. Therefore, reflexive increased cardiac output must be distributed adequately to supply various tissues with sufficient resources. For the brain this is particularly important, as neural tissue is not compatible with ischaemia but the restricted

space within in the cranium limits continuous increases in blood-supply (Smith and Ainslie [2017](#)).

1.4.1 Cerebral blood flow, oxygenation, and metabolism during physical activity

At rest, the brain consumes $\approx 20\%$ of whole-body oxygen supply (Ogoh and Ainslie [2009](#)). Thus, a fractional portion of whole-body mass requires a substantial portion of total cardiac output (Ogoh and Ainslie [2009](#)). During graded exercise of increasing intensity, transcranial doppler measurements of the internal carotid artery reveal that blood velocity, and cerebral blood flow (Brassard et al. [2010](#)), increases as a function intensity (Smith and Ainslie [2017](#)). However, the relationship between cerebral blood flow and exercise intensity is not linear. Instead, cerebral perfusion increases from rest and thereafter drops below baseline/resting measurements once intensity exceeds $80\% \text{VO}_{2\text{Max}}$ (Secher, Seifert, and Van Lieshout [2008](#); Ando et al. [2011](#)). Cerebral oxygenation, the difference between oxygen supply and oxygen use (oxygenated haemoglobin – deoxygenated haemoglobin), follows the same trend. Graded exercise increases measured oxygenation but at high intensities ($> 80\% \text{VO}_{2\text{Max}}$), cerebral oxygenation is marginally lower than at rest (Querido and Sheel [2007](#); Secher, Seifert, and Van Lieshout [2008](#); Lucas et al. [2010](#)). Therefore, exercise intensity is a moderating variable of cerebral metabolism. One explanatory mechanism has been proposed by Sato et al. ([2011](#)), who showed that flow rate of the external carotid artery increases when cerebral blood flow declines, suggesting that thermoregulation is prioritised. Second, high physical intensities likely induce cerebral vasoconstriction once the second ventilatory threshold is surpassed and resultant hyperventilation decreases PaCO_2 (arterial partial pressure and content of CO_2) (Lucas et al. [2010](#); Smith and Ainslie [2017](#)).

Cerebral metabolism of substrate must therefore be altered accordingly with changes in blood flow and oxygenation. The global consumption of substrate (glucose equivalent grams consumed per minute) increases exponentially from rest to maximal intensity (Smith and Ainslie [2017](#)). Expectantly, the neuronal activity needed to sustain frequent and maximal muscular contractions exceeds neuronal activity at rest or leisurely intensities. The proportion of consumed substrate, however, is inverted. Peak glucose consumption is observed at rest and light intensities where metabolism is predominantly (98-100%) oxidative (Ogoh and Ainslie [2009](#); Smith and Ainslie [2017](#)). Once exercise intensity increases to moderate and maximal intensities, cerebral uptake of lactate increases up to 10-fold and one-third of global cerebral metabolism is non-oxidative (Secher, Seifert, and Van Lieshout [2008](#); Lucas et al. [2010](#)). Hence, lactate produced

from intense physical activity supplies an essential substrate for cerebral metabolism, playing a role in sustaining neural outputs (Smith and Ainslie [2017]). Taken together, intense physical activity demands increased global metabolism from cerebral tissue which operates with restricted perfusion (Secher, Seifert, and Van Lieshout [2008]; Ando et al. [2011]; Smith and Ainslie [2017]). Changes in cerebral metabolism during intense activity likely moderates the continuation, reduction, or cessation of muscular outputs. But more importantly, provides the foundational rational of the relationship between physical activity and cognitive functioning. If cerebral tissue is operating in a distinct metabolic window, with reduced perfusion and increased metabolic demand, neural outputs of movement are likely prioritised over metabolically costly cognitive outputs (Dietrich and Audiffren [2011]).

Evidence of compromised cognitive function due to physical stress, however, has been equivocal. A consistent observation is that physical stress can improve parameters of cognitive function (Reviewed by Lambourne and Tomporowski [2010]). Although in line with physiological measurements of perfusion and oxygenation, at exceedingly high intensities the cognitive benefits of exercise appear to reverse (Dietrich and Audiffren [2011]; McMorris [2016]). Lucas et al. ([2012]) were among the first to simultaneously measure cognitive function and cerebral perfusion during exercise. At rest, increased middle cerebral blood flow was associated with improved cognitive performance in the Stroop task (Lucas et al. [2012]). During exercise (cycling at 30% and 70% of predicted heart rate maximum) however, response time and accuracy improved, but was not correlated with cerebral blood flow or oxygenation (Lucas et al. [2012]). A prolonged bout of 50-minutes cycling also showed persistent improvements in Stroop task performance compared to rest, despite cerebral perfusion steadily decreasing as the bout progressed (Ogoh et al. [2014]). Therefore, changes to cognitive function during exercise are not solely explained by cerebral perfusion and metabolism. The multifaceted relationship between exercise intensity, duration and modality on widespread cognitive abilities must be explained by several interacting mechanisms and ongoing research.

1.4.2 Arousal and the Inverted-U hypothesis

Early theories surrounding cognitive psychology described the role of exercise-induced arousal. Yerkes, Dodson, et al. ([1908]) initially proposed the inverted-U hypothesis, which posits that stressors increase the state of arousal in the brain, improving performance. Until excessive stress and hyper arousal causes interference – resulting in a stress-performance curve resembling an inverted-U. Davey ([1974]) later adopted this theory to exercise, where physical intensity describes the state or level of stress. Hence,

at rest the state of arousal is low, light-moderate intensities increase arousal and cognitive performance exists on a positive slope (Davey [1974]). Crossing an intensity threshold results in declined cognitive performance and a negative relationship with further increases in intensity (Davey [1974]). Arousal in this sense refers to excitatory behaviour of neurons, where increased arousal lowers the excitatory thresholds needed to achieve neural impulses (Davey [1974]; McMorris [2016]). Further, it is argued that arousal narrows the focus of attentional mechanisms, thus limiting the representation of irrelevant cues/stimuli (Davey [1974]; McMorris [2016]). The inverted-U hypothesis has remained a focal point of research and several studies have adopted methodologies of graded increases in physical intensity to elucidate the arousal threshold.

1.4.3 Catecholamine Hypothesis

The catecholamine hypothesis developed on theories of exercise-induced arousal, proposing a neurochemical mechanism of the inverted-U effect. Cooper ([1973]) used animal models to link acute increases of peripheral noradrenaline in response to physical stress, with increased concentrations of noradrenaline in the brain. Plasma concentrations of noradrenaline are also shown to increase from the anticipation of upcoming physical stress, providing more time to take effect (Cooper [1973]; Wann, Audet, and Anisman [2010]). Thus, it was posited that catecholamines released in response to exercise, increases activity of the reticular formation of the brainstem, heightening states of arousal (McMorris [2016]). Adrenal-derived catecholamines have subsequently been shown to increase concentrations of neurotransmitters throughout the brain, particularly the PFC (Miyashita and Williams [2006]; Velasquez-Martinez, Vazquez-Torres, and Jimenez-Rivera [2012]). A function of the autonomic nervous system and hypothalamus during exercise is to activate the sympathoadrenal system (SAS)(Borer [2003]). The SAS stimulates endocrine release of adrenaline and noradrenaline from the adrenal medulla (Borer [2003]). The circulating catecholamines then bind to afferent vagal β -adrenoreceptors, which innervates the nucleus tractus solitarii of the blood-brain barrier and ultimately the locus coeruleus (Miyashita and Williams [2006]). Excitation of the locus coeruleus increases the cerebral synthesis and release of noradrenaline and dopamine, neurotransmitters that collectively modulate neuronal activity (Velasquez-Martinez, Vazquez-Torres, and Jimenez-Rivera [2012]).

The noradrenergic and dopaminergic pathways amplify or dampen neuronal signals to synergistically modulate the signal to “noise” ratio in the PFC (Arnsten [2011]). Exocytosis of noradrenaline binds to three primary receptor targets, α_1 -adrenergic, α_2 -adrenergic and β -adrenergic each class consisting of three known subvariants (Roth

et al. [1988]. β -adrenergic activation amplifies downstream neural activity through the synthesis and activity of cyclic adenosine monophosphate (cAMP) (Roth et al. [1988]; Bondi, Jett, and Morilak [2010]). While α_2 -adrenergic binding has opposing effects, inhibiting cAMP activity by competitive binding of GTP-binding proteins (Roth et al. [1988]). Finally, α_1 -adrenergic binding effects a separate intracellular signalling pathway (phosphatidylinositol-protein kinase) to reduce neural firing rates (Bondi, Jett, and Morilak [2010]).

Dopamine has two receptor targets, D_1 -like receptors consisting of D_1 and D_5 subvariants (El-Ghundi, O'Dowd, and George [2007]). And D_2 -like receptors which have three known subvariants (D_2 , D_3 and D_4). D_1 -like receptors amplify neuronal activity, like β -adrenergic receptors, through cAMP activation (El-Ghundi, O'Dowd, and George [2007]). Similarly, D_2 -like binding inhibits cAMP activity through competitive binding, akin to α_2 -adrenergic receptors (El-Ghundi, O'Dowd, and George [2007]). Therefore, the receptors with highest affinity are preferred and activated first when neurotransmitter concentrations in the brain increase in response to exercise (Leh, Petrides, and Strafella [2010]; Arnsten [2011]). The inhibitory receptors, α_2 -adrenergic and D_1 -like, have highest affinity to noradrenaline and dopamine respectively, and act to dampen firing to irrelevant stimuli (Leh, Petrides, and Strafella [2010]; Arnsten [2011]). Thus, aiding preferred stimuli to reach adequate summation - facilitating signal-noise ratios (Arnsten [2011]; McMorris [2016]). However, excessive catecholamine release and neurotransmitter concentrations result in activation of low-affinity receptors, interfering with optimal neuronal signalling (McMorris [2016]).

Both the duration and intensity of physical stress moderate peripheral catecholamine release (Borer [2003]). Therefore, both factors should be considered when conceptualising neurotransmitter response and changes in cognitive functioning. There is an exponential increase in peripheral catecholamine concentrations during incremental exercise taken to exhaustion (McMorris et al. [2003]; Dalsgaard et al. [2004]). At low workloads/intensities, concentrations remain close to baseline measures (McMorris et al. [2003]; Dalsgaard et al. [2004]). Crossing an intensity threshold, believed to be near 75% VO_{2Max} , results in an exponential increase in plasma noradrenaline and adrenaline concentrations (McMorris et al. [2003]). The exponential increase in catecholamines is also correlated with exceeding the individuals' lactate threshold (Podolin, Munger, and Mazzeo [1991]). However, physical stress above 40% VO_{2Max} but below the lactate threshold, which persists for more than 30-minutes, can elicit a similar excessive catecholamine response (Hodgetts et al. [1991]). Distinct from low intensity physical stress

($\approx 30\%$ $\text{VO}_{2\text{Max}}$), which after 4-hours does not increase plasma catecholamine concentrations to the same magnitude (Hodgetts et al. 1991). Taken together, heavy exercise performed above the lactate threshold or 75% $\text{VO}_{2\text{Max}}$ or, moderate intensity exercise exceeding 30-minutes, can elicit exponential increases in central neurotransmitter concentrations (Borer 2003; McMorris 2016). In turn, this may result in a deterioration of cognitive performance once a catecholamine and neurotransmitter threshold is surpassed – aligned with the inverted-U hypothesis.

Numerous studies corroborate the predicted facilitation of cognitive function at sub-maximal intensities. At $40\text{--}50\%$ $\text{VO}_{2\text{Max}}$ or equivalent, faster response times have been reported in the Stroop (Yanagisawa et al. 2010; Endo et al. 2013), Stop Signal (Joyce et al. 2009), Flanker (Davranche, Hall, and McMorris 2009; Kamijo et al. 2009), Choice Response (Davranche et al. 2005) and N-back (Hogan, Mata, and Carstensen 2013) task paradigms. Importantly, no difference in accuracy or error-rates were reported in these studies, indicating overall facilitation of cognitive functioning. When intensity is increased to $60\text{--}70\%$ $\text{VO}_{2\text{Max}}$ or equivalent, improved response times are reported across task paradigms of Choice Response and Detection (McMorris et al. 2003; Guizani et al. 2006; Ozyemisci-Taskiran et al. 2008; Pesce and Audiffren 2011), Tower of London (Chang et al. 2011; Hung et al. 2013) and unnamed visual attention tasks (Pesce et al. 2007b; Pesce et al. 2007a; Tsai et al. 2014). Apart from prolonged protocols ($>1\text{-hour}$) where reduced speed and accuracy was reported in central executive tasks by Moore et al. (2012). In summary, there is extensive evidence that physical stress, approximately below an individual's lactate threshold, supports arousal to improve working memory, attention and central executive proficiency. However, at maximal intensities the predicted deterioration of cognitive performance has not been consistently proven.

When intensity is increased to $80\text{--}100\%$ $\text{VO}_{2\text{Max}}$ or volitional failure, mixed cognitive efficiencies are reported. Response times improved in Choice Reaction and Detection (Guizani et al. 2006), decision making in a soccer-specific tests (McMorris and Graydon 1996; McMorris and Graydon 1997; Fontana et al. 2009) and improved accuracy in working memory (Griffin et al. 2011). Contrasting findings have been reported with reduced performance in Choice Reaction (Delignières, Brisswalter, and Legros 1994; Chmura and Nazar 2010), Detection (McMorris and Keen 1994; Brisswalter et al. 1997; Coco et al. 2009) and reduced accuracy in set shifting tasks (Thomson, Watt, and Liukkonen 2009). Finally, no differences in cognitive functioning at baseline/rest and extreme (100% peak power) exercise conditions have also been reported (Kamijo et al. 2004a; Kamijo et al. 2004b; McMorris et al. 2005; Griffin et al. 2011). The conflicting findings are somewhat explained by the non-homogenous protocols across

studies. Exercise modalities and studied populations are mixed, criteria for reaching fatigue or measuring $\text{VO}_{2\text{Max}}$, maximal workloads and subsequently the duration of activity varied.

Lambourne and Tomporowski (2010) conducted a meta-regression analysis of 40 studies and concluded that a key predictor of cognitive performance is the timing of assessment. That is, in dual-task protocols where cognitive functioning is measured during the exercise condition – cognitive performance is inhibited (mean effect size = -0.14). When the acute effect of physical activity is measured i.e., cognitive functioning is assessed immediately following the exercise condition – cognitive performance is improved (mean effect size = 0.20) (Lambourne and Tomporowski 2010). Therefore, impairments to cognitive functioning associated with exercise are transient, although circulating catecholamines remain elevated (McMorris et al. 2003). Further, compared to cycling, treadmill running appears to cause greater impairments to cognitive functioning (Lambourne and Tomporowski 2010). Altered cognitive efficiency during exercise must be further explained by a transient mechanism which also accounts for different exercise modalities, influencing the computational cost of coordinating movement.

1.4.4 Reticular Activating Hypofrontality Model

Dietrich and Audiffren (2011) proposed the reticular activating hypofrontality (RAH) model which applies haemodynamic and resource allocation theories to the exercise-cognition interaction. The model posits that reticular activation (arousal) is a causative factor of improved cognitive performance during exercise. But, rather than performance following an inverted-U profile with variables of intensity or duration, it is hypothesised that the efficiency of cognitive domains diverge (Dietrich and Audiffren 2011; Audiffren 2016). That is, exercise-induced arousal facilitates implicit information processing, at the expense of explicit processing efficiency (Dietrich and Audiffren 2011; Audiffren 2016). Where the underlying mechanism of inhibited explicit processing efficiency is hypofrontality – reduced resource/substrate delivery to the PFC (Dietrich and Audiffren 2011; Audiffren 2016).

The RAH model theorises that during states of physical stress the brain must prioritise finite metabolic resources (Dietrich and Audiffren 2011; Smith and Ainslie 2017). Therefore, due to the computational cost of coordinating movement (described above in a batting context), areas of the brain which are least associated with sustaining neuromuscular outputs, forfeit metabolic priority (Dietrich and Audiffren 2011). Hence, the associative, integrative functions of the PFC are inhibited by reduced blood flow,

allocating more resources (glucose particularly) to dense neural matter of the cerebellum and motor cortex (Dietrich and Audiffren [2011](#)). The proposed mechanism of hypofrontality expands on earlier theories with some key distinctions. First, the modality of exercise influences the computational cost of movement which then exacerbates the metabolic compensations imparted on the PFC. Hence, the observation that running causes greater cognitive impairment than cycling, is explained by the increased computational costs of balance, posture and whole-body movement (Dietrich and Audiffren [2011](#)). Second, the PFC is hypothesised to have compensatory mechanisms to maintain performance with restricted substrate (Ogoh and Ainslie [2009](#); Dietrich and Audiffren [2011](#)). Therefore, it is argued that prolonged hypofrontality depletes compensatory reserves and modulates cognitive efficiencies (Dietrich and Audiffren [2011](#)).

The steady depletion of compensatory reserve results in hierarchical downregulation of explicit processing efficiency, rather than a collapse in cognitive efficiency described by inverted-U theorists (Dietrich and Audiffren [2011](#)). Explicit information processing streams which are most demanding of attentional and metabolic resources will be lost first, while implicit processing is increasingly favoured (Thompson [2013](#)). Finally, hypofrontality is transient (Dietrich and Audiffren [2011](#)). The cessation of exercise results in a sudden loss of computational load in large volumes of neural matter responsible for coordinating movement (Lambourne and Tomporowski [2010](#); Audiffren [2016](#)). Thus, the metabolic compensations and cognitive deficiencies related to hypofrontality can be suddenly lifted. Explicit processing efficiency should therefore be most vulnerable during exercise (Lambourne and Tomporowski [2010](#); Audiffren [2016](#)). While circulating catecholamines and reticular activation remain heightened following the cessation of exercise, explaining observations of improved implicit and explicit functioning immediately following exercise (McMorris et al. [2003](#); Ogoh and Ainslie [2009](#); Lambourne and Tomporowski [2010](#)).

Empirical evidence of hypofrontality caused by physical stress is limited. Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) scans supply highest accuracy but preclude any head-movement. Hence, studies reporting 18F-fluorodeoxyglucose PET scanning describe regional glucose metabolism within the PFC from the cessation of exercise (La Fougere et al. [2010](#); Shimada et al. [2013](#)). Nonetheless, Higuchi et al. [2001](#) have demonstrated that glucose metabolism in the PFC is likely decreased while running. Near-infrared spectroscopy (NIRS) is a newer technique that is less sensitive to movement (Ferrari and Quaresima [2012](#)). The refraction of light through the forehead is used to quantify changes in oxygenated and deoxygenated haemoglobin concentration (Ferrari and Quaresima [2012](#)).

Oxygenated haemoglobin is believed to be a marker of neural activation (Scholkmann et al. [2014]) and the difference between oxygenated and deoxygenated haemoglobin is an indicator of overall cerebral oxygenation (Shibuya et al. [2004]).

Using NIRS, hypofrontality has been reported during graded cycling to exhaustion, where PFC oxygenation decreases near 80% $\text{VO}_{2\text{Max}}$ (Tempest, Eston, and Parfitt [2014]; Oussaidene et al. [2015]) or 75-100% peak power output (Subudhi et al. [2008]; Subudhi et al. [2009]). Taken together there is empirical substance for the theoretical cognitive predictions of the RAH model. Physical stress moderates glucose metabolism in the PFC and it can be argued that compensatory reserves will continually deplete if activity persists (Dietrich and Audiffren [2011]). While increased intensity above 80% $\text{VO}_{2\text{Max}}$, where global cerebral blood flow becomes restricted (Smith and Ainslie [2017]), results in further reductions to PFC substrate delivery (Tempest, Eston, and Parfitt [2014]; Oussaidene et al. [2015]), exacerbating cognitive deficiencies. The impact of dynamic, whole-body exercise is predicted to exacerbate hypofrontality, but to date has not been fully studied.

The haemodynamic and neurochemical impact of physical stress must have some influence on prolonged batting performance. Run scoring requires physical effort which will impart measurable consequence to cognitive functioning. The numerous tactical evaluations and psychomotor control required to effectively intercept deliveries must therefore not be negatively affected by modulated cognitive efficiencies. And increased run scoring rates may further modulate the physical stress of an innings which also appears to affect cognitive functioning.

1.4.5 Influence of prolonged cognitive exertion on physical performance

Cognitive or mental fatigue can be described as the decline of performance in processing tasks, particularly involving the central executive (Ishii, Tanaka, and Watanabe [2014]). The psychobiological state is believed to be induced by prolonged self-regulation, but exact mechanisms are unclear. Resource theories have implicated the depletion of glucose (Gailliot et al. [2007]) and phosphocreatine (Roelands et al. [2020]). Although the role of glucose is questioned, as the substrate does not appear to be significantly consumed by repeated cognitive efforts (McKenna et al. [2012]). More prominent theories link neural mechanisms with motivation and the anticipation of reward. Ishii and colleagues Ishii, Tanaka, and Watanabe ([2014]) describe a regulation system where cognitive performance is regulated by the balance of activation in dual systems.

The mental facilitation system, consisting of the frontal cortex, limbic system, basal ganglia, and thalamus – heightens cognitive performance (Ishii, Tanaka, and Watanabe [2014]). While the mental inhibition system, comprised of the insular cortex and posterior cingulate cortex, maintains cerebral homeostasis by restraining cognitive performance (Ishii, Tanaka, and Watanabe [2014]). Both systems are active during acute cognitive workloads and ultimately motivational input determines the activity of the facilitation system, balancing dual system activity (Ishii, Tanaka, and Watanabe [2014]). Therefore, repeated, or prolonged cognitive efforts, require increased motivation to outweigh the inhibition system and maintain task performance (Ishii, Tanaka, and Watanabe [2014]). Cognitive fatigue and motivation are particularly important then, in the sporting environment where physical stress is present.

Induced cognitive fatigue has been shown to interfere with physical performance (Van Cutsem et al. [2017]; McMorris et al. [2018]; Habay et al. [2021]). Importantly, the physical parameters of heart rate, lactate metabolism and oxygen uptake are comparable in mentally fatiguing and control conditions. Hence, the variable associated with reduced physical performance in individuals displaying cognitive fatigue, is increased perceived exertion (McMorris, Barwood, and Corbett [2018]). Thus, cognitive efforts are considered to form part of the regulation of physical performance computed by a “central governor” as discussed previously (Noakes, Gibson, and Lambert [2005]; McMorris, Barwood, and Corbett [2018]). Where increased cognitive exertion results in executive inhibition of motor outputs to maintain a performance equilibrium from the individuals anticipated tolerable level of overall exertion (Noakes, Gibson, and Lambert [2005]; Marcora, Staiano, and Manning [2009]).

Recently a model encompassing mental and physical effort with performance regulation has been proposed by McMorris ([2021]). Building on the dual regulation system (Ishii, Tanaka, and Watanabe [2014]), it is argued that the perception of effort cost is computed from four factors (McMorris [2021]). Prior experience of similar exercise (or in this case batting bouts), prior experience of similar cognitive loads, perception of fitness/readiness and motivation (McMorris [2021]). Thus, motivation (personal goals, desire to compete, perception of importance etc.) plays a role in attenuating the individual’s perception of effort and therefore moderates task performance/output (Marcora, Staiano, and Manning [2009]; McMorris [2021]). Mental fatigue (reduced cognitive output/performance) is therefore observed when the perception of cost/effort exceeds the perception of available resources (McMorris [2021]). Or reward value is relatively low, resulting in subpar motivation to balance the dual regulation system in favour of facilitation (Ishii, Tanaka, and Watanabe [2014]; McMorris [2021]).

Regardless of mechanism, an apparent consequence of mental fatigue is impaired sport-specific psychomotor performance (Habay et al. 2021). One investigation in cricket induced mental fatigue in batters using a prolonged Stroop task intervention (Veness et al. 2017). The mental fatigue condition resulted in batters running between the wickets (two runs) significantly slower ($p = 0.002$, $d = -0.51$) than the control condition (Veness et al. 2017). Ratings of perceived exertion were also elevated ($p < 0.001$, $d = -7.82$), compared to control, in the mentally fatigued condition when batters performed identical physical tests (Veness et al. 2017). To our knowledge, no study has investigated the isolated cognitive workload of batting. Hence, it is unclear if prolonged batting imparts a cognitive workload which results in cognitive fatigue. Although, as this review has tried to demonstrate, a batting innings requires prolonged cognitive control and executive functioning, which is an accepted criteria of inducing mental fatigue (Ishii, Tanaka, and Watanabe 2014; Habay et al. 2021). Further, in a competitive batting innings, the cognitive cost of batting is not isolated from physical stress.

Current literature has required that variables of physical stress are isolated to elucidate cognitive consequences and vice versa, cognitive workloads are standardised to investigate latter physical outputs. A batting innings, therefore, resembles territory in research which has received little attention. Physical and cognitive performance simultaneously direct task performance in a multifaceted fatigue relationship. We hypothesise that as physical intensity moderates cognitive performance (Dietrich and Audiffren 2011; McMorris 2016). And cognitive workloads influence an individual's psychobiological perception internal resources (Noakes, Gibson, and Lambert 2005; McMorris 2021) – run scoring intensity moderates the observed fatigue profile of a batting innings through this interaction.

1.5 Cricket Specific Exercise Protocols – Replicating the Sporting Environment

To explore the intricate relationship between cognitive, psychophysical, and physical variables, it is important to carefully trace the cricketing environment. The modality and intensity of exercise influences the onset and degree of fatigue experienced by the athlete (Ament and Verkerke 2009). Even if the modality of exercise is matched, there is no substitute to investigate the workload of a marathon which can replace a 42.2km running intervention. Sport-specific exercise protocols are therefore developed to replicate the unique demands of competitive match play in controlled environments or training. For example, rugby is a contact sport and the BURST protocol, developed from time-motion analysis of match play, prescribes running intensities and distances

interspersed with rucks, mauls, and tackles (Roberts et al. 2010). Thus, to investigate sport specific hypotheses, researchers and practitioners can induce a realistic workload of match play with one athlete and minimal equipment. Cricket is an ideal candidate for tailored protocols as competitive matches are documented, providing accurate and detailed retrospective data.

Two batting protocols are currently published. Referenced previously in this review, Vickery et al. (2013) reported the physiological characteristics of a small-sided cricket match named Battlezone (Previously described by Renshaw et al. (2010)). The protocol requires a batting pair to compete against bowling pairs in six bouts. Bowlers are rotated every eight overs (1 bout) and placed in the field of 27.4m diameter, equivalent to the inner ring of a standard cricket field (Vickery et al. 2013). A total of eight players (including two batters) are competing in an innings length of 42 overs (Vickery et al. 2013). The physical workload of Battlezone can be considered a limitation of the protocol. The batting pair compete against less fielders than a standard match (five vs ten) and on a restricted field. Hence, the availability and frequency of run scoring is likely inflated compared to competitive innings. Vickery, Dascombe, and Duffield (2014) confirmed that the physical workload of batters during Battlezone exceeded that of traditional ODI's, producing significantly greater mean heart rates ($d = 0.61$) and blood-lactate concentrations ($d = 1.14$). Further, total distance covered ($d = 1.32$) and mean speeds ($d = 1.24$) of batters during Battlezone were significantly increased compared to ODI's accompanied with increased perceived exertions ($d = 0.58$) (Vickery, Dascombe, and Duffield 2014). Therefore, for batting specific hypotheses related to fatigue, Battlezone may not be optimal. Although the ecological replication of competition against rotating bowlers is valuable.

The second batting protocol, developed by Houghton and colleagues (Houghton et al. 2011; Houghton, Dawson, and Rubenson 2011), replicates an individual innings of 100 runs in the ODI format. Developed from time-motion analysis and ball-by-ball match data, BATEX prescribes run scoring requirements and running intensity for a 30-over centre wicket simulation. The simulated innings is divided into six phases, each consisting of five overs. The phases are 'Building momentum', 'Taking initiative', 'Fighting back', 'Power play', 'Maintaining tempo', and 'Closing out the innings' each designed to replicate the fluctuations of run scoring intensity in an organic, competitive innings (Houghton et al. 2011; Houghton, Dawson, and Rubenson 2011). At the beginning of every over, an audiotape dictates the required runs and run types for the over e.g., one boundary + one double shuttle. The batter then faces deliveries, usually projected

from a bowling machine, and chooses when to run based on achieved contacts. Therefore, the workload is standardised so that each over requires an equal distance covered, and the intensity is prescribed to maximum speed in phases 2, 4 and 6 (Houghton et al. 2011; Houghton, Dawson, and Rubenson 2011). While remaining phases, 1, 3 and 5 are performed at a 'self-selected cruise' speed.

Finally, the interim between deliveries and overs is calculated from the mean elapsed period between successive deliveries of competitive matches - regulating the physical intensity of the protocol (Houghton et al. 2011; Houghton, Dawson, and Rubenson 2011). When compared to a competitive innings, batters cover moderately less distance ($2171 \pm 157\text{m}$ vs $2476 \pm 631\text{m}$) in the BATEX protocol (Houghton et al. 2011), although the main differentiator ($d = 1.61$) is increased distance at low intensities/walking in ODI's (Houghton et al. 2011). The standardised workload of BATEX allows researchers and practitioners to analyse the responses of batters repeatedly and reliably to a match-realistic scenario (Houghton et al. 2011).

There are other factors of the sporting environment which should be considered when replicating a batting innings. Not only should the physical demands be simulated, but also the cognitive and contextual factors that influence performance. Physically, batters must handle intense periods of sprinting between the wickets and repeated high-intensity movement. However, the cognitive load is just as crucial, involving rapid decision-making, shot selection, and anticipating the bowler's tactics in real-time. Replicating certain aspects of a batter's decision making processes should be considered in a simulated innings. Additionally, contextual elements such as field placements, pitch conditions, and the psychological pressure of match scenarios can be incorporated. For example, BATEX attempts to provide physiological pressure by dictating run scoring requirements. Other contextual factors, like field placements, also provide opportunity to introduce cognitive challenges to a batting simulation.

This literature review explored the physical stress experienced by cricketers while batting. Studies reveal that batting induces significant physiological strain due to frequent high-intensity efforts involving rapid acceleration and deceleration. Key stressors include musculoskeletal strain, particularly in the lower-limbs and biceps femoris. Further, the cognitive determinants of successful batting are discussed to develop theory on how physical stress may impact cognitive domains which are relevant to batting. Intercepting successive deliveries with high precision requires sustained attention and neuromuscular control. Batting performance, therefore, requires a combination of physical exertion and cognitive acuity - a fatigue profile which is not well studied.

The determinants of batting success are difficult to measure in a controlled environment. Protocols like BATEX have allowed researchers to begin testing how batters of different skill levels perform and manage the demands of an innings. There remains scope, however, to further elucidate differences in batting skill from graded exercise protocols or simply increasing the variety of validated protocols. It may also be advantageous to increase the complexity of simulated innings where the criteria for successful/desired interceptions can be manipulated. Or, providing forms of incentive/consequence, ultimately adding layers of ecological validity and the transferability of data from controlled environments to the field. Despite its popularity, twenty20 cricket is an area of cricket which has received least attention to date. Considering BATEX fulfils a 30-over individual innings from a format which is also less physically intense (Petersen et al. 2010), batting protocols which are tailored to the dynamics of a Twenty20 innings are required. It is plausible that the increased run scoring intensity of Twenty20 cricket accounts for the difference in physical intensity. However, how run scoring intensity moderates the responses of batters is yet to be directly studied.

Chapter 2

Simulating a Twenty20 Innings - Phase 1

The novel Twenty20 innings simulations presented in this chapter are published in the journal: F1000Research. An open peer-review system is used by the journal and reviewer comments for version one of the manuscript can be viewed online - (<https://doi.org/10.12688/f1000research.52783.2>). At the time of writing, version two has been published which addresses comments and suggestions made by reviewers and final review is pending.

This chapter serves as the foundation for the repeated measures laboratory study conducted on skilled batters in subsequent chapters. To investigate the impact of run scoring rates on the physiology of the batter, a method of exposing batters to adequate and comparable stimulus is required. The aim of the chapter was to develop the ‘average’ representation of two individual batting innings’ which are distinguishable by striking rate but, identical in variables of duration, deliveries faced and partnership contribution. Hence, within the methodology chapters III and IV, the published manuscript is referenced.

Contribution of Authors;

T Lopes - conceptual design, data retrieval and analysis, visualisations and writing

D Goble - conceptual design, supervision

S Kerr - supervision, proof-reading and editing

B Olivier - supervision, proof-reading and editing

Novel Twenty20 Batting Simulations: A Strategy for Research and Improved Practice¹

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Abstract

Twenty20 cricket and batting in particular have remained vastly understudied to date. To elucidate the effects of batting on the batter, tools which replicate match play in controlled environments are essential. This study describes the development of two Twenty20 batting simulations, a high and low strike rate innings, generated from retrospective analysis of international and domestic competition. Per delivery analysis of probabilities of run-type and on/off-strike denomination produce ball-by-ball simulations most congruent with retrospective competitive innings. Further, both simulations are matched for duration and dictated through audio files. The ‘high’ strike rate innings requires a batter to score 88 runs from 51 deliveries, whereby 60 runs are from boundaries. Similarly, the ‘low’ strike rate innings requires a batter to score 61 runs from 51 deliveries where 27 runs are scored from boundaries. Because batting simulations dictate run scoring outcomes, a method of quantifying a batter’s performance from bat-ball contact scores is described. Ten elite batters achieved a mean performance score of 72 (SD = 26) and 88 (21) for the low and high strike rate simulations respectively. This study provides sport practitioners with a training technique to improve specific skill acquisition and enables research in understudied Twenty20 batting.

Keywords: Cricket, batting performance, simulation, innings

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2.1 Introduction

Batting in the sport of cricket is an interceptive task which creates a combination of physical (Johnstone and Ford [2010]; Pote and Christie [2016b]) and cognitive stress (Goble and Christie [2017]). In a cricket match, runs are scored by sprinting between the wickets or by hitting the ball out of play (boundaries). During an innings, a batter and batting partner will attempt to accumulate runs, while trying to avoid being dismissed. Resultantly, a batter's innings may be prolonged resulting in fatigue (Christie, Todd, and King [2008]; Johnstone and Ford [2010]) which may adversely affect batting performance. Traditional net-practice however, may not replicate the physical demands of an innings produced in competitive match-play (Goble and Christie [2017]; Vickery et al. [2018]). Batters in practice may therefore not routinely experience batting under appropriate fatigue (Vickery and Nichol [2020]), despite evidence suggesting that "practice how you play" methodologies are beneficial to skill-acquisition. In cricket, the availability of competitive match data enables the development of detailed innings simulations that can be an effective addition to practice programmes. And a reliable method of recreating the physiological baseline of competitive batting for further scientific inquiry.

In previous studies, attempts to replicate a batting innings have taken various forms. Christie, Todd, and King ([2008]) replicated the physical demands of batting through shuttle running. Running multiple shuttles, the length of a cricket pitch (17.68m), physically mimics run scoring in cricket. However, shuttle running protocols neglect to account for the energetic cost of ball striking and boundaries where no shuttles are required. As a result, more sophisticated protocols which require batters to intercept deliveries were subsequently developed. The Battlezone protocol mimics a small-sided cricket match reduced to eight players and six repeated bouts, each consisting of eight overs (Vickery et al. [2013]). Batters are required to compete in a bout against two bowlers and four fielders in a 27m ring. However, the limited length (six overs per batting pair) and smaller field may limit the transferability of this protocol to elite sport and its validity for research. Finally, the BATEX (Houghton et al. [2011]) protocol simulates scoring a One Day International (ODI) century (100 runs) with ball-by-ball audio guidance. In this protocol batters are required to complete an innings of two hours and 20 minutes, the typical length of an ODI century (Houghton et al. [2011]). Unlike the Battlezone protocol which provides batters with freedom to score runs at any rate, BATEX instructs batters on the denomination of runs required – singles, doubles or boundaries – every over. Thus, BATEX mimics the amount of time spent at the crease and also allows the innings to follow a run scoring progression akin to

centuries scored in ODI's. Further, the BATEX protocol is divided into phases which allows researchers and sport practitioners to manipulate scoring zones and running intensities throughout the innings creating variability to the batters information sources and match realism (Pinder et al. 2011; Woods et al. 2019). However, the BATEX protocol being a simulation of the ODI format, may not be applicable to the increasingly popular, shorter Twenty20 format where an entire team innings is often completed within two hours.

To date no batting protocol has specifically aimed to address a Twenty20 innings. Batting may be performed at various run scoring intensities (strike rate) depending on the context of the innings and format of the game. Twenty20 cricket is the shortest format of the game (20 overs per side) resulting in higher run scoring intensities as batters attempt to score more runs from fewer available deliveries. Resultantly, a Twenty20 innings imposes unique movement demands compared to longer game formats (Petersen et al. 2010; Sholto-Douglas et al. 2020) and may require different approaches to batting technique (Noorbhai 2020b; Jamil et al. 2022). Thus, batting simulations which are unique to Twenty20 cricket are required. Further, the BATEX protocol places minimal emphasis on the role of the batter's partner. As batting is performed in pairs, consideration for how runs are scored while the batter in question is off-strike is necessary as this increases the workload placed on the batter.

This study aimed to develop two Twenty20 batting simulations which mimic the demands of competitive match play. To further highlight the impact of strike-rate, both simulations possess an equal number of deliveries, resulting in varying run scoring intensities throughout the innings.

2.2 Materials and Methods

Two Twenty20 simulations were developed to simulate match play for an individual achieving a 1) 'high' and 2) 'low' strike rate innings. Both high and low strike rate simulations are equal in duration, achieved by standardizing the number of deliveries in both simulations. However, the strike rate and mode of run scoring in either innings varies in accordance with data obtained from selected innings. Relevant retrospective innings selection procedures and accessed databases are outlined in Figure 2.1.

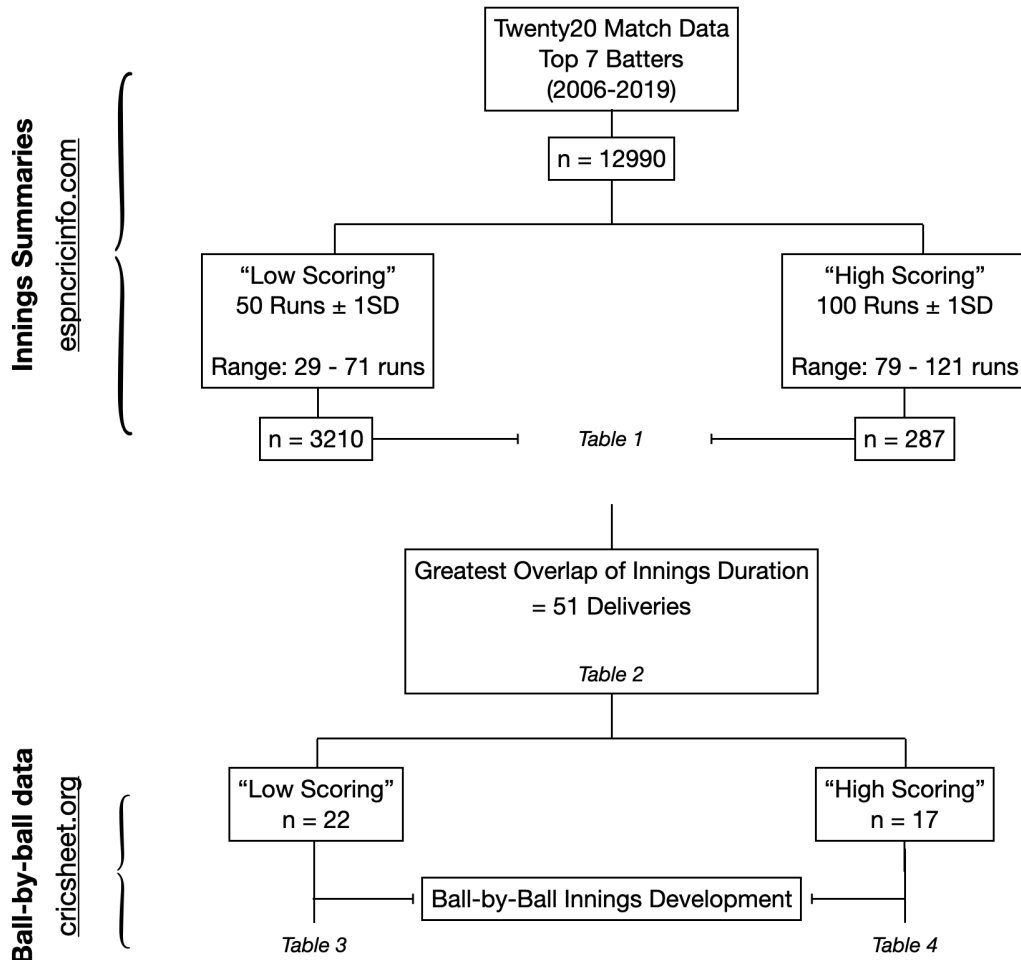


FIGURE 2.1: Schematic outline of data reduction procedures and relevant innings selection from online databases. Table 2.1 provides innings summaries of specialist batters within each ‘low’ and ‘high’ scoring subcategory. Table 2.2 provides refined innings summaries from each ‘low’ and ‘high’ subcategory with an equal number of on-strike deliveries. Table 2.3 and Table 2.4 represent the developed ball-by-ball simulations.

2.2.1 Retrospective data acquisition – Innings summaries

Match data from previous Twenty20 internationals (2006–2019) and the domestic Vivo Indian Premier League (IPL) competition (2008–2019) were exported from ESPN-cricinfo ([Cricket Records - Find ICC Cricket Stats Online — ESPNcricinfo.com](https://www.espncricinfo.com)) using an Excel macro. ESPN’s statistical database provides match summaries and run tallies of team and individual innings. Individual innings were filtered to only include specialist batters (top seven batters). Thus, a total sample of 12990 individual innings were selected. These innings represented 5906 different batters, runs mean = 19.9 (SD = 21.2).

Two batting milestones, a half-century (50 runs) and century (100 runs), were selected to represent a ‘low’ and ‘high’ strike rate threshold. These milestones were selected as they represent meaningful team contributions and secondly, are likely to be of a duration which warrants physiological study. From the 12990 innings, 87 innings produced exactly 50 runs scored and only nine innings matched the 100 run criteria. Therefore, to increase the sample sizes around the chosen milestones, a range of ± 1 standard deviation of runs scored (SD = 21.2 runs) was applied. Thus, the half century (low strike rate) sample size increased to $n = 3210$ and included innings of 29–71 runs scored. Likewise, the century (high strike rate) sample size increased to include innings ranging from 79–121 runs scored, producing an $n = 287$. The innings summaries for these adjusted milestones are presented in Table 2.1.

TABLE 2.1: Average characteristics of individual innings milestones broadened by ± 1 SD of runs scored

	‘low’ strike rate (50 runs $\pm$ 1SD)			‘high’ strike rate (100 runs $\pm$ 1SD)		
	Mean (SD)	Median	Range	Mean (SD)	Median	Range
Runs scored	44.2 (11.5)	42	29–71	91.1 (10.3)	89	79–119
On-strike deliveries	31.8 (9.9)	31	8–79	52.9 (8.6)	53	25–119
Minutes at the crease	48 (17)	46	7–109	78 (14)	81	37–109
Fours ^a	4.1 (2.1)	4	0–12	8.5 (2.8)	8	1–16
Sixes ^b	1.7 (1.4)	1	0–9	4.7 (2.5)	5	0–13
Strike rate ^c	147 (39)	139	67–422	177 (30)	171	123–194

Data represent competitive individual innings produced in Twenty20 internationals and the Vivo Indian Premier League between 2006–2019. Innings milestones are broadened to categorize a range of ± 1 SD (21 runs) around the given milestone, increasing the number of innings within each category. ‘low’ strike rate $n = 3210$ individual innings, ‘high’ strike rate $n = 287$.

^a Intercepted delivery which leaves the field of play with a minimum of one bounce, batter credited four runs

^b Intercepted delivery which leaves the field of play without a bounce, batter credited 6 runs

^c Run scoring intensity - fraction of runs scored and on-strike deliveries

The number of on-strike deliveries was selected as a robust measure of innings length. To standardize the duration of both batting simulations, frequency distributions of deliveries faced within each innings subset were drawn and the point of intersection with the largest sample size between the ‘high’ and ‘low’ strike rate innings was identified. The resultant overlap occurred at 51 deliveries faced, with a total of 27 half-centuries (‘low’) and 18 centuries (‘high’). While these innings were of equal duration, it is important to note that fundamental differences in runs scored, strike rate, number of boundaries and ratio of boundaries to runs accumulated by running - define the intensity of each simulation. Therefore, to account for each of these factors and to develop accurate simulations, ball-by-ball match data was needed to provide record of how each individual innings (‘low’, $n = 27$ and ‘high’, $n = 18$) progressed and how runs were accumulated throughout the innings.

2.2.2 Innings Development – Ball-by-ball Match Data

Ball-by-ball data was obtained from a second online database (Rushe 2009). However, at the time of analysis, existing ball-by-ball match data from the online database reduced our sample to 22 ‘low’ and 17 ‘high’ strike rate innings – presented in Table 2.2.

TABLE 2.2: Average characteristics of broadened innings milestones at the point of greatest overlap in number of on-strike deliveries

	‘low’ strike rate (n = 22)			‘high’ strike rate (n = 17)		
	Mean (SD)	Median	Range	Mean (SD)	Median	Range
Runs scored	61.3 (8.9)	65	39–71	90.4 (11.1)	89	79–117
Minutes at the crease	61 (14)	60	51–101	76 (14)	81	55–112
Fours ^a	5.4 (2.4)	6	1–10	8.5 (2.9)	9	4–15
Sixes ^b	1.8 (1.5)	1	0–5	4.4 (2.9)	4	1–13
Strike rate ^c	120 (18)	128	76–139	177 (22)	175	154–229

Data represent competitive individual innings produced in Twenty20 internationals and the Vivo Indian Premier League between 2006–2019 with a standardized workload of 51 on-strike deliveries.

^a Intercepted delivery which leaves the field of play with a minimum of one bounce, batter credited four runs

^b Intercepted delivery which leaves the field of play without a bounce, batter credited 6 runs

^c Run scoring intensity - fraction of runs scored and on-strike deliveries

Match data was downloaded as comma separated variables (CSV’s) and reduced to isolate the relevant innings within the match. These CSV’s were imported into an R script for analysis. The purpose of analysing ball-by-ball innings data was to determine,

i) the deliveries with the highest frequency of dot balls, singles, two's, three's, fours and sixes, ii) how runs were accumulated and, iii) the scoring rates of each individual innings. Furthermore, because batting is performed in pairs, each innings was analysed for its respective partnership data to determine; i) the average partnership deliveries faced and hence the overall duration of the simulation, ii) the number of deliveries which the batter is most likely on-/off-strike and, iii) the proportion of runs scored by the batter's partner. By analysing ball-by-ball data, the average number of dot balls, singles, two's, three's, fours and sixes were calculated for both the 'low' and 'high' strike rate innings.

For each individual innings, the role of the batter's partner was determined using a second R script. Ball-by-ball partnership data was extracted from the match data for every delivery faced by the batter's partner/s. This provided the number of deliveries faced during the innings as well as the sequence of runs scored by the batter's partner/s. Like the development of the high and low scoring innings, the length of the overall partnership (deliveries faced by both batter and partner/s) was determined by the point of greatest overlap in overall partnership length from the representative high and low scoring innings. However, three overlaps were identified each with a sample size of one. As a result, the overlap which was nearest to the median of deliveries faced for the overall partnership was chosen as the best representative of the partner's role in both high and low strike rate simulations. This overlap was identified as 43 deliveries resulting in a total simulation length of 94 deliveries. To determine which of the total 94 deliveries the batter is on strike for, a strike score was calculated for every delivery by assigning a '1' if the batter was on-strike and '0' if the batter was off-strike for every innings. Thereafter, each delivery was scored using Equation [2.1](#).

$$\left(\frac{Ball\ No.}{P.\ Length} \right) \times Strike\ Score \quad (2.1)$$

Whereby, 'Ball No.' is the sequenced number of the delivery in question (e.g. one, two, ... 94), 'P. Length' denotes the partnership length or number of deliveries within the given partnership and 'Strike Score' denotes the assigned binary score given to the delivery whether the batter was on-strike (1) or off-strike (0). The median was calculated for each delivery and rounded up to identify each ball number (of all 94 deliveries) the batter will be on strike for. This procedure was completed for both simulations.

Once on-/off-strike deliveries were determined, assigning runs to deliveries completed the development of the simulations. For on-strike deliveries, the number of dot balls,

singles, two's, three's, fours and sixes were tallied for every delivery (independently for high scoring and low scoring simulations) to determine which deliveries produce the highest frequency/probability of each possible score. From these probabilities run types (dot ball, one, two... etc.) were assigned in descending order of probability. In the case where deliveries produced identical probabilities for two or more run types, priority was given to the run type with the least overall frequency in the innings (for example, sixes were prioritized over dot balls) Lastly, because dictating the exact outcome of each delivery is not representative of match play, every six deliveries (one over) required run types were grouped giving batters freedom to decide which on-strike delivery, within an over, will produce a given run type according to the stroke played. As studying effects of batting partner/s is not a primary outcome of the batting simulations, required runs from off-strike deliveries were made identical for both high and low scoring simulations. Using the same method described for on-strike deliveries, run type was assigned to each off-strike delivery.

2.2.3 Simulated Innings Task Design

Time motion analysis of Vivo IPL Twenty20 matches was performed and determined the average interval between deliveries to be 35 seconds and 80 seconds between overs, consistent with findings of Houghton et al. (2011). An audio recording was created using a written script and computer text-speech function (Supplementary Material 1, 2) to govern intervals between overs/deliveries. Further, the audio recording describes; i) when the batter is on-/off-strike ii), the run requirements for each over and their denomination (singles, doubles, boundaries etc.) iii) an indication of the start and end of each over.

During each on-strike delivery, the batter is free to select which on-strike deliveries to score from and what run type is achieved from a given delivery. The only constraints placed are that the batter must match the run type with the achieved stroke and that all required shuttles for an over must be achieved. To match run type with achieved stroke for a given delivery, batters are required to penetrate a scoring zone to be awarded 'four' and bat-ball contact must be achieved for all other run types. However, if the number of on-strike deliveries remaining in an over are near-depleted, shuttles may be enforced regardless of achieved contact or scoring zone penetration. For a '1' batters should complete a single shuttle (17.68m) likewise, for '2's batters should complete a double shuttle, and three shuttles for a '3'. For all shuttles, batters are required to complete a 90° turn at the end of the crease when completing the final shuttle for a given delivery. Boundaries will require one and a half shuttles for a 'four'

and no shuttles for a ‘six’. When the batter is off strike, instruction from the audio tape will dictate the required shuttles necessary for each off-strike delivery and the batter will complete these shuttles beginning on the audio cue. After necessary shuttles have been completed the batter will walk back to the striking crease. Shuttles must be run at maximum intensity akin to match play where batters attempt to maximize the number of runs scored from every delivery.

To improve the ecological validity and dynamics of the simulations, three phases were introduced to represent how an innings would develop under match conditions. A ‘PowerPlay’ phase of six overs and two phases of five overs each namely; ‘Middle’ and ‘Close Innings’ phase. During these phases, fielding positions or scoring zones can be altered to present varying scoring zones to encourage the batter to manipulate the ball into different areas of the field/arena. In cricket, the Powerplay consists of six overs whereby a maximum of two fielders are placed outside the inner ring while the remaining overs allow a maximum of five fielders outside the inner ring (ICC 2021). No more than five fielders may be placed on the ‘leg-side’ throughout the innings (ICC 2021). Therefore, we suggest a reduction in the number of available scoring zones following the ‘PowerPlay’ phase and discretion in the remaining number and placement of zones depending on the desired objectives of the simulation and skill of the batter.

To incentivise the batter and provide a form of match pressure, an overall batting performance score can be obtained according to the method of Müller and Abernethy (2008). Briefly, the method entails tallying bat-ball contacts according to three criteria. Good ball contact requires contact on the face of the bat and the ball deflecting in the intended direction (2 points). Bad ball contact entails contact with the bat and the ball deflects into an unintended direction (1 point). One point is deducted for an unsuccessful attempt at contact (-1 point) and a ‘leave’ entails an intentional lack of contact with the ball (1 point). The achieved score for a given delivery is doubled if the stroke penetrates a scoring zone. If a batter is dismissed, the final achieved batting score is halved, with further deduction factors applied for multiple dismissals (i.e. Two dismissals; performance score divided by three). Batters are instructed to bat for a maximized performance score by ensuring optimal bat-ball contacts, manipulating deliveries into pre-assigned scoring zones as often as possible and avoiding a loss of wicket. Attempting to achieve a maximal performance score in the simulation places a form of pressure on the batter improving match realism. According to the batting performance score criteria, a maximum score of 4 points may be achieved per on-strike delivery resulting in a maximum simulation score of 204 points from 51 on-strike

deliveries.

The method was piloted in a controlled study and recruited 10 experienced (competitive playing experience > 6 years) batters who bat in the top 7 of their respective teams. Participants were required to be currently competing in amateur cricket leagues and free from injury (age: 22.3 (SD = 3.4) years, stature: 178 (8) centimetres, mass: 80.9 (9.0) kilograms). Procedures were reviewed by the Human Research Ethics Committee (clearance no: M180872) and participants signed informed consent. An arena schematic and procedural outlines are provided in Figure 2.2. Participants completed both batting simulations, in a randomised order, separated by a minimum of 48 hours. A regulation size indoor/action cricket arena with artificial playing surface was used and deliveries projected from an electric bowling machine Figure 2.2. Batters wore full protective kit (leg, pads, gloves, helmet) and faced deliveries projected at $110 \text{ km} \cdot \text{h}^{-1}$ directed at off-stump with lateral movement away from the batter. Deliveries were not permuted for the purpose of this study. In the PowerPlay phase, four scoring zones (2.5 meters wide) were placed in positions to mimic fielding gaps at third-man, extra cover, mid-wicket and long-on. Scoring zones were demarcated with coloured cones placed on the ground visible to batters who were also verbally informed to their placement and changes throughout the simulation. Once the PowerPlay phase was concluded, one scoring zone (third-man) was removed to increase the difficulty of achieving boundaries in the ‘Middle’ and ‘Close Innings’ phase.

2.3 Results

The developed simulations are 1 hr 2 min in duration and provided in audio format for ease of accessibility (supplementary material 1, 2). Ball-by-ball run requirements and on-strike delivery numbers, within an over, are presented in Table 2.3 (‘low’ strike rate innings) and Table 2.4 (Century ‘high’ strike rate innings). The low strike rate simulation requires a batter to score 61 runs at a strike rate of 120, whereby 27 runs are scored through boundaries. The ‘high’ strike rate simulation requires a batter to score 88 runs at a strike rate of 173, whereby 60 runs are scored through boundaries.

In the half-century innings, batters achieved a batting performance score mean (SD): 72 (26) points, while the century produced a mean (SD): 88 (21). Table 2.5 presents by-phase summaries of both simulations and achieved performance scores adjusted to percent scores with associated point multipliers (scoring zone placement) and deductions (play-and-miss).

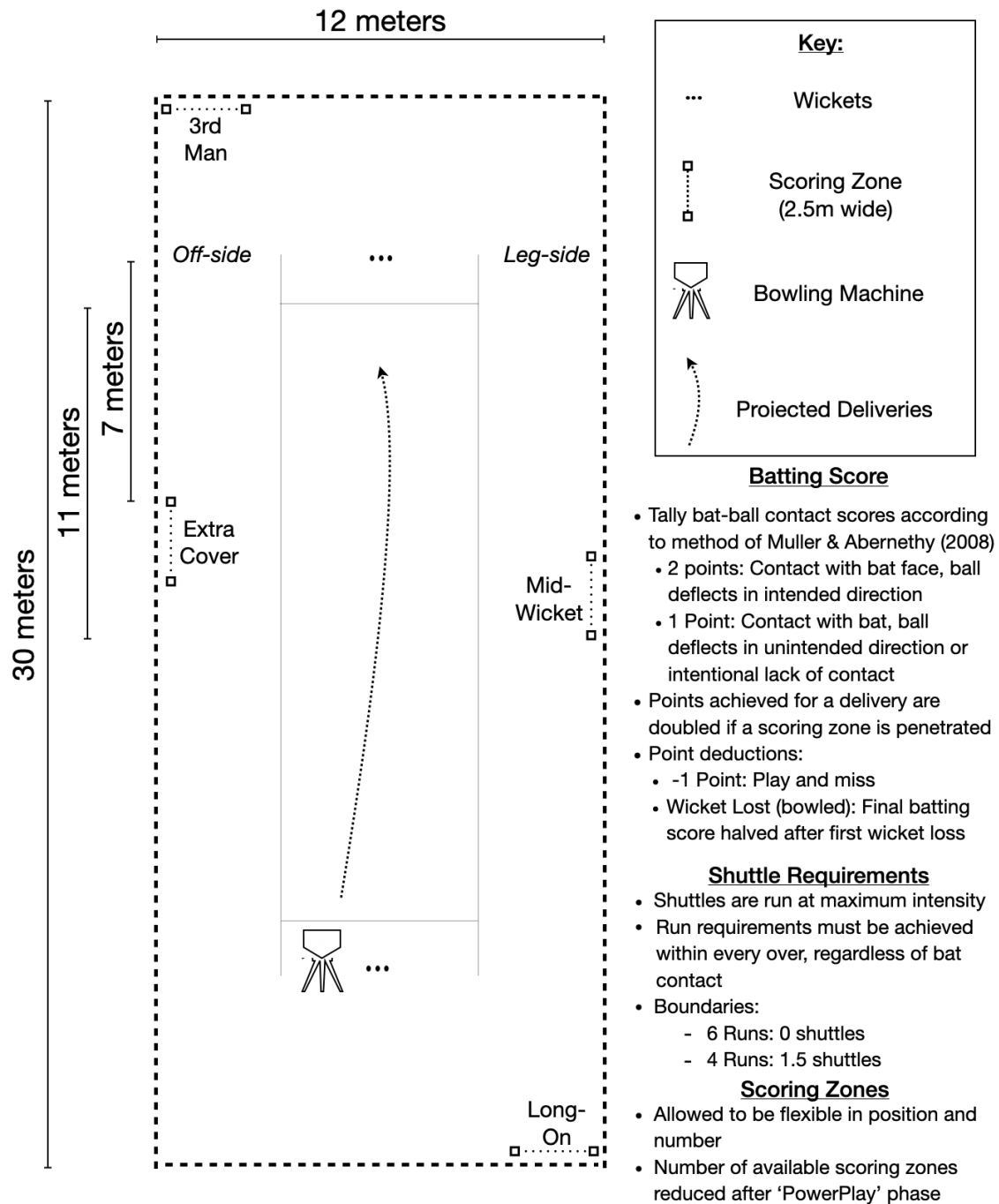


FIGURE 2.2: Procedural outline and arena schematic (drawn to scale) depicting regulation size action/indoor cricket arena and regulation length pitch (17.68m).

TABLE 2.3: Ball-by-ball simulation of a Twenty20 ‘low’ strike rate innings (50 runs $\pm$ 1SD)

Phase	Over No.	On-strike delivery No.	Run Requirements	
			On-strike	Off-strike
PowerPlay	1	1, 4, 6	0, 0, 0	0, 1, 0
	2	1, 3, 5, 6	4, 0, 0, 0	0, 3
	3	2, 3, 4, 5	0, 0, 4, 0	0, 1
	4	1, 4, 6	0, 0, 1	4, 0, 0
	5	2, 4, 6	0, 0, 2	0, 0, 0
	6	1, 3, 6	1, 0, 0	1, 4, 1
Middle	7	1, 2, 3, 4	1, 1, 0, 0	4, 0
	8	1, 2, 4	1, 1, 1	4, 1, 1
	9	1, 2, 4, 6	1, 0, 2, 4	0, 1
	10	2, 4, 6	1, 1, 4	4, 1, 0
	11	1, 3, 4, 6	2, 6, 1, 2	1, 0
Close Innings	12	2, 3, 6	0, 1, 1	0, 0, 0
	13	2, 4, 6	2, 1, 1	1, 0, 0
	14	1, 5, 6	1, 1, 1	1, 4, 0
	15	3, 4, 6	1, 4, 6	1, 2, 0
	16	2	0	1, 2, 1

Ball-by-ball audio dictation provided in supplementary material 1.

2.4 Discussion

This study has developed two comprehensive batting simulations which are unique to Twenty20 cricket. A ball-by-ball description of a high and low strike rate individual innings but varying in strike rate and requirement of boundaries are detailed ball-by-ball. Additionally, we suggest a method of improving the ecological dynamics and validity of batting simulations. These considerations improve match realism allowing researchers to produce match representative data and a tool for sport practitioners to bolster training programmes.

Previous studies have investigated the physiological costs of scoring an ODI century (Goble and Christie [2017](#); Houghton et al. [2011](#); Pote and Christie [2016b](#)) or the effect of shuttle running volume (Christie, Todd, and King [2008](#)) on a batter’s physiology. However, the simulations developed in this study provide researchers with the necessary tools to investigate Twenty20 batting in a more comprehensive manner. Namely, the simulations developed in this study may highlight the impact run scoring intensity (strike rate) on the batters’ physiology which previously was not possible. Additionally, compared to shuttle running protocols and net practice, batting simulations as

TABLE 2.4: Ball-by-ball simulation of a Twenty20 ‘high’ strike rate innings (100 runs $\pm$ 1SD)

Phase	Over No.	On-strike delivery No.	Run Requirements	
			On-strike	Off-strike
PowerPlay	1	1, 3, 5	0, 0, 4	0, 1, 0
	2	1, 3, 4,	1, 4, 0	0, 3, 0
	3	2, 3, 4, 6	0, 0, 1, 1	1, 4,
	4	1, 2, 3, 5	0, 4, 1, 4	0, 0
	5	1, 2, 5	1, 0, 0	0, 0, 0
	6	1, 4, 6	0, 1, 0	1, 4, 1
Middle	7	1, 5, 6,	6, 1, 0	4, 0, 4
	8	1, 3, 4	1, 1, 4	1, 1, 1
	9	1, 2	1, 1	1, 4, 1, 0
	10	1, 2, 3, 5, 6	1, 2, 1, 0, 1	1
	11	2, 3, 5	2, 1, 1	0, 0, 0
Close Innings	12	2, 3, 4, 6	2, 6, 4, 6	0, 1
	13	2, 4, 6	1, 6, 1	0, 0, 1
	14	2, 3, 5	1, 0, 1	4, 0, 1
	15	1, 3, 6	4, 2, 4	2, 0, 1
	16	1, 2	4, 0	2, 1

Ball-by-ball audio dictation provided in supplementary material 2.

described in this study, provide a more accurate representation of the stressors imposed on a batter during match play (Goble and Christie [2017](#); Vickery et al. [2018](#)).

Several theories of skill acquisition attest to the benefit of utilizing realistic game scenarios in training. The idea can be traced to Thorndike ([1913](#)) who developed identical elements theory. In essence, it is proposed that motor learning is enhanced when characteristics of practice and competition are most interchangeable. Beyond learning, another view termed the Specific Adaptation to Imposed Demands (SAID) principle proposes that physiological adaptations are sensitive to stressors (Reilly, Morris, and Whyte [2009](#)). Taken together, practice design in sport should consider its transferability into competition which can be achieved by simply mimicking aspects of competition. Araujo and Davids ([2016](#)) further advise on avenues which could be explored such as, psychological (coping with internal representations of match pressure, performance anxiety etc.), motor – the physical and muscular stress associated with an innings. Finally, perceptual and cognitive, which would relate to the batters ability to understand the implications of a bowling/fielding change or identifying the kinematic identities of an off-spinners stock and variation deliveries (Araujo and Davids [2016](#);

TABLE 2.5: Innings simulation summary and mean batting performance parameters from 10 experienced, top order batters

Innings	‘low’ strike rate (50 runs $\pm$ 1SD)			‘high’ strike rate (100 runs $\pm$ 1SD)		
Phase	PowerPlay	Middle	Close Inn.	PowerPlay	Middle	Close Inn.
On-strike deliveries	20	18	13	20	16	15
Required strike rate	60	161	154	110	150	280
Scoring zone placements *	3.5	3.1	1.2	3.3	2.5	2.9
Point deductions †	2.3	1.6	0.9	2.5	1.4	0.8
Performance score §(%)	44.4	47.6	44.6	43.5	46.7	48.8

* Intercepted deliveries which penetrate demarcated scoring zones - bat-ball contact score multiplied by two

† 1 point deducted for every failed attempt at ball contact

§ Bat-ball contact scores tallied and adjusted for maximum available points (4 points per on-strike delivery)

Müller et al. [2019](#)). Importantly though, when designing representative training tasks according to this framework, careful consideration should be taken in understanding the constraints present in competition as these constraints govern performance in the competitive environment. Training should provide opportunities for athletes to learn actions/responses which combat constraints as they present in competition. For example, centre-wicket simulations, like BATEX and those described in our study, recreate psychological constraints of coping with fatigue, coupled with a limited number of deliveries to achieve a targeted tally of runs and a further constraint on where runs are available with the use of scoring zones. The constraints present dynamically, akin to competitive innings’, and practitioners can respond to an athletes performance in a given simulation by restricting the number or placement of scoring zones, encouraging new responses and ultimately facilitating learning (Pinder et al. [2011](#); Araujo and Davids [2016](#)).

In contrast, the simulations in this study critically lack a component of representative design due to the use of a projectile bowling machine. The temporal constraints of intercepting a high-velocity delivery exemplifies another scenario where batting skill is specific to perceptive variables of the competitive environment. Put simply, skilled batters alleviate temporal constraints by anticipating characteristics of upcoming ball-motion before the ball is released (Abernethy and Russell [1984](#); Müller, Abernethy, and Farrow [2006](#); Müller, Brenton, and Mansingh [2021](#)). To achieve this, batters perceive kinematic variables in the bowler’s action and generate responses according to these availing kinematic cues. Therefore, a batters responding stroke is coupled with his/her perception of the bowlers action, particularly the bowling arm and shoulder (Müller, Abernethy, and Farrow [2006](#)). When deliveries are projected from a bowling machine, these perceptive variables are eliminated from the batting task, altering how batters infer future events from present cues (ecological validity) is reduced (Araujo,

Dauids, and Passos (2007); Woods et al. (2019). Pinder, Renshaw, and Dauids (2009) demonstrated that batters do in fact alter their behaviour when intercepting deliveries projected from a bowling machine compared to live bowlers. Practice centred around bowling machines is therefore sub-optimal for learning and skill transfer to the competitive environment for the same reason traditional net practice, even with live bowlers, fails to replicate the numerous constraints present in competition. Although we have shown projectile bowling machines provide a convenient workaround for practitioners to implement training tasks which highlight often neglected constraints, the use and misuse of such equipment should be noted. A further enhanced representative learning design could see live bowlers competing against a single batter performing either the low or high strike rate simulation.

Batting simulations dictate run requirements thus, losing the metric of runs scored as a valuable measure of performance and incentive. To account for this, we implemented a method which objectively quantifies the batter's performance from bat-ball contacts, stroke placement and dismissals. Batters achieved similar scores in both simulations (Table 2.5) which may indicate a ceiling of skill set for our sample at the time of investigating or a lack of sensitivity in our scoring method. Future research should identify additional variables which may contribute to batting performance scores that are representative of skill. Further developing a dependable method of scoring batting performance will benefit both researchers and coaches. Sport practitioners can also adjust details of the Twenty20 simulations such as, the number and placement of scoring zones or setting batting performance score targets to create varying demands of difficulty for different athletes. However, Innings simulations are naturally limited in flexibility because run scoring outcomes and on/off-strike denominations are dictated. As a result, effectiveness for skill acquisition and the batter's interest may reduce with repetition. To alleviate this, additional simulations which highlight unique game dynamics namely, recovering from a sudden loss of multiple wickets or catering to specific batting order positions could be developed.

Conclusion Batting research in cricket requires intricate methods of replicating the stressors and demands of an individual innings. By doing so, the physiological effects of batting on the batter may be investigated while also providing a tool for specific skill acquisition. The simulations developed in this study replicate an hour-long partnership consisting of 51 on-strike deliveries and played at either a high or low strike rate. Batters produced similar scores in both the high and low strike rate innings when quantifying their performance based on bat-ball contacts and stroke placement. Utilizing these simulations should provide an enhanced training stimulus to traditional

net-based practice while future research investigates other factors that contribute to a batters performance.

Disclosure statement

The authors declare no conflicts of interest

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Images of Laboratory Design

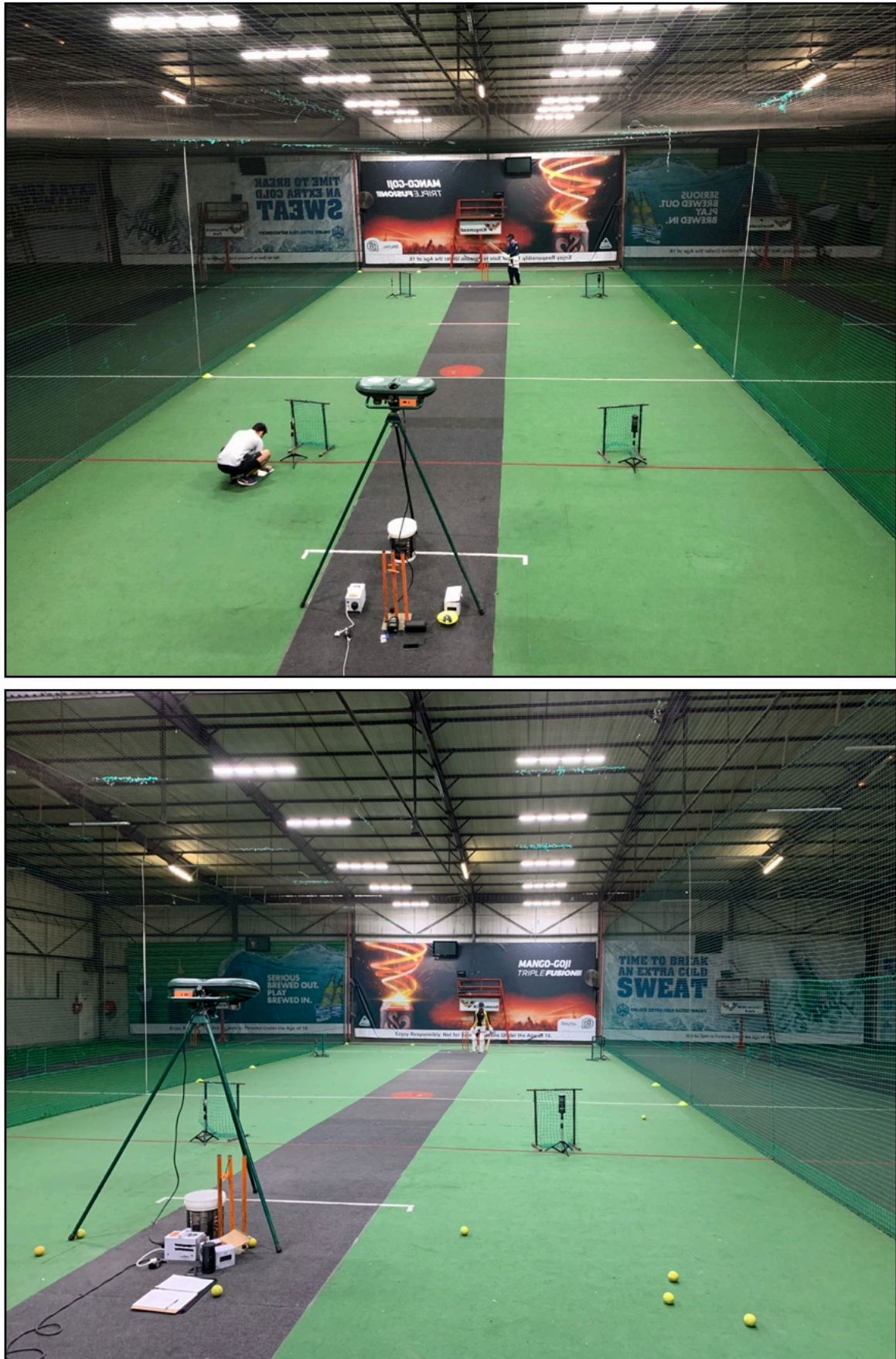


FIGURE 2.3: Birds-eye view and floor-level image of indoor testing-arena. Sprint-time infrared gates and deflectors placed protected by net barriers



FIGURE 2.4: Pilot testing early iterations of the Pitch Reaction Test



FIGURE 2.5: Participant completing cognitive assessments prior to batting bout. CogState test battery recording user responses to cognitive tests (groton-maze learning task) and second laptop recording raw spectroscopy data from the fNIRS head-band

Chapter 3

The Physical Stress of Twenty20 Batting - Phase 2

When comparing match formats (tests v ODI v T20), previous research has indirectly implied that run scoring rates influence the physical strain of a batting innings. However, no study has directly investigated the of impact varying strike rates on the physiology of the batter. Especially in Twenty20 cricket, where increased strike rates are clearly favourable for competitiveness.

This chapter aimed to address this gap in literature. Defining the physical strain of batting in at a ‘low’ or ‘high’ strike rate. It is also useful to compare the physical strain measured in our novel innings simulations against previously reported variables from competitive matches. Defining how the physical strain induced by novel Twenty20 simulations compares with previously reported outcomes, provides additional context when interpreting cognitive findings.

Contribution of Authors;

T Lopes - conceptual design, data collection and analysis, data visualisations and writing

D Goble - conceptual design, supervision

S Kerr - supervision, proof-reading and editing

B Olivier - supervision, proof-reading and editing

The physicality of a Twenty20 batting innings is marginally augmented by strike rate

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Abstract

This study aimed to highlight the effect of run scoring intensity (strike rate) on physical exertion during an individual Twenty20 innings. In a randomised cross-over design, fourteen experienced top-order batters (mean $\pm$ SD: age 22.3 $\pm$ 3.4 years; competitive playing experience 15 $\pm$ 4 years; lean body mass 70.8 $\pm$ 8.8 kg) completed two Twenty20 simulations of equal duration but varying intensity - mimicking a high (173) and low (120) strike rate innings. The high strike rate innings produced greater heart rates overall ($\beta = 153$ (SE = 2.8) vs 148 (2.6) beats $\cdot$ min $^{-1}$, $p < 0.01$) and slower sprint performance ($\beta = 2.64$ (SE = 0.40) vs 2.55 (0.43) seconds, $p < 0.01$). However, the low strike rate innings induced more deterioration to sprint performance as the innings progressed ($\beta = 0.02$ seconds per over, $p < 0.01$) but lower-limb peak power output appears preserved following either innings ($p = 0.08$). Reductions to body mass were comparable (0.7 vs 1%, $p = 0.71$) as was accumulation of blood lactate across phases of the simulations ($p = 0.67$). Run scoring intensity augments the stress of a Twenty20 innings. A batters ability to maintain high striking rates, especially in the latter phases of an innings, may depend on delaying the onset of reduced muscular output associated with fatigue.

Keywords: cricket; simulation; innings; fatigue; workload

3.1 Introduction

Batting in the sport cricket is a physically demanding motor task (Stretch, Bartlett, and Davids [2000]; Scanlan et al. [2016]) which has recently gained attention in literature. During an innings, batters will attempt to score large run totals competing against ten fielders and bowlers in rotation. The physical stress of run scoring is two-fold. Ball-striking requires the complex arc of a cricket bat (Noorbhai [2020a]) to be completed within millisecond temporal constraints (Land and McLeod [2000]; Stretch, Bartlett, and Davids [2000]) where strength is an advantage (Noakes and Durandt [2000]; Taliep, Prim, and Gray [2010]). To be credited runs, intercepted deliveries need to leave the field of play (boundaries) or if the stroke remains in play, batters run between the creases of the “wicket” (a length of 17.68m) before the intercepted delivery is collected and returned by fielders. Subsequently, the high intensity linear accelerations required to complete runs/shuttles enforces eccentric contractions (Thompson, Nicholas, and Williams [1999]) known to alter muscular structure and performance (Pull and Ranson [2007]; Highton, Twist, and Eston [2009]). A prolonged batting innings therefore induces fatigue (Noakes and Durandt [2000]; Christie, Todd, and King [2008]) which may hinder batting performance (Goble and Christie [2017]). However, the combined effects of ball-striking and running between the wickets have seldom been investigated.

An individual innings can be prolonged to multiple days in test cricket or condensed into a few hours in the shorter one-day or Twenty20 formats. Subsequently, investigating a batting innings has taken various forms. Research first highlighted the impact of running between the wickets (Christie, Todd, and King [2008]; Pote and Christie [2016b]; Christie et al. [2019]). Notably, a short seven over bout has been shown to reduce eccentric and concentric strength of the lower limb musculature by 10–18% (Christie et al. [2019]). Further, the authors observed that running volume was associated with strength loss as high-volume interventions incurred greater strength deficits compared to moderate volumes – especially to flexors of the knee (Christie et al. [2019]). Resultantly, only high running volumes (12 shuttles per over) were found to be detrimental to sprint performance, indicating that higher run scoring intensities will induce more muscular damage and fatigue (Highton, Twist, and Eston [2009]; Christie et al. [2019]). However, in a typical competitive innings runs are scored intermittently rather than at predictable high or moderate workloads. To account for this, more elaborate innings simulations have been developed to mimic both the timing of deliveries and the natural progression of run scoring (Houghton et al. [2011]; Vickery et al. [2013]). The BATEX simulation (Houghton et al. [2011]) mimics the scoring of a century (100 runs) in the 50-over, One Day International (ODI) game format. In response to BATEX, detriments

to sprint performance have also been documented (Goble and Christie [2017]) confirming the cost of run scoring to muscular output. Further, heart rates in excess of 140 beats per minute (Houghton, Dawson, and Rubenson [2011]; Pote and Christie [2016b]; Goble and Christie [2017]) and blood lactate concentrations $> 4.0 \text{ mmol} \cdot \text{L}^{-1}$ (Houghton, Dawson, and Rubenson [2011]) indicate a substantial metabolic stress for the two-hour innings. However, research has also observed that different formats (multi-day, ODI and Twenty20) will induce varying demands on the batter (Petersen et al. [2010]; Vickery et al. [2018]; Sholto-Douglas et al. [2020]). For example, total distances covered by batters appear to be similar in ODI's and Twenty20's but, in the latter format more distance was covered sprinting and striding (Petersen et al. [2010]). Thus, further research is needed to investigate the nuances of batting in Twenty20 cricket.

Twenty20 cricket is the fastest format to produce a result – achieved by limiting both team innings' to 120 deliveries (20 overs). The condensed format has gathered interest, evidenced by the increasing number of Twenty20 tournaments played globally. Resultantly the number of fixtures played in a competitive season have increased, ultimately increasing the workload placed on athletes (Orchard et al. [2010]; Orchard et al. [2015]). Injury risk and player welfare has therefore been questioned (Soomro et al. [2018]) but the physicality of Twenty20 cricket and batting particularly has remained vastly understudied. Batting in a Twenty20 also imposes a unique challenge. To produce competitive totals, batters need to maximise on the limited number of deliveries by scoring at increased intensities (strike rate). Batting at high strike rates inherently requires more risks and boundary striking, however research is yet to elucidate how this impacts the batter.

This study aimed to quantify the physical stress of batting in a Twenty20 at a low and high strike rate. To highlight the impact of strike rate, a randomised cross-over laboratory design investigated experienced batters in two simulations: a high and low strike rate innings. We hypothesized that high run scoring intensities would augment the physical stress imposed on the batter and therefore cause more deterioration to physical performance.

3.2 Materials and Methods

3.2.1 Study Design and Setting

This study implemented a randomised, cross-over laboratory design including one introductory and two experimental sessions. The introductory session was mobile to aid

in participant recruitment and experimental sessions were conducted in an indoor batting arena (length = 30 meters, width = 12 meters). The order of experimental sessions were randomly assigned and batters were aware that both sessions would be of equal length but otherwise blinded to the differences between simulations and objectives of the study.

3.2.2 Participants

We recruited 14 experienced, skilled batters (represented at national or domestic level) with more than six years of competitive playing experience. Batters had to be free from injury in the six months prior to the study and currently competing in competitive (amateur or semi-professional) leagues. The investigation was conducted during a competitive season to ensure batters were match fit. Upon recruitment participants signed voluntary informed consent. All procedures were reviewed by the Human Research Ethics Committee (clearance no: M180872)

3.2.3 Instrumentation and Outcome Measures

Mass and stature were assessed using a digital scale (Elektra, Bolzano, Italy) and meter stick to the nearest 0.1kg and 0.5cm, respectively. Lean body mass and body fat percentage were determined from the Jackson and Pollock (Jackson and Pollock 1985) sum of seven skinfolds using callipers (Harpندن, Sussex, United Kingdom). To sub-maximally estimate maximum aerobic capacity (VO_{2Max}), a constant workload step-test using a 41cm box and metronome as described by (McArdle et al. 1972; Chatterjee et al. 2004) was implemented to assess heart rate recovery. Heart rate was recorded from a Polar RS800CX wristwatch and chest strap (Polar Electro, Kempele, Finland) to calculate VO_{2Max} (McArdle et al. 1972; Chatterjee et al. 2004)

In experimental sessions, sweat rate was calculated from change in mass measured with and without kit using a digital scale to the nearest 0.1kg (Elektra, Bolzano, Italy). To quantify aerobic stress, heart rate was recorded from a Polar RS800CX wristwatch and chest strap (Polar Electro, Kempele, Finland). Further to inform anaerobic stress, blood lactate concentration was obtained using a lancet and Lactate Pro2 handheld analyser (CosMed, Rome, Italy). Infrared timing gates (FusionSport, Sydney, Australia) placed two meters from either crease were used to assess sprint times performed while run scoring in the batting simulations. Finally, peak power output was assessed from a maximal vertical jump test using a force mat (FusionSport, Sydney, Australia). Peak power output was assessed from two jump methods, countermovement jump and the squat jump. A third variable, Eccentric Utilization Ratio (EUR) was

calculated from the ratio of peak power outputs of the countermovement jump and squat jump (McGuigan et al. 2006).

3.2.4 Procedures

In the introductory session, participants were introduced to the study objectives and instructed of their requirements in the following experimental sessions. Anthropometry was collected. Skinfold sites included the dominant side: chest, mid-axilla, tricep, subscapularis, suprailliac, abdominal and quadricep. The maximum aerobic capacity test was performed at a stepping rate of 24 cycles per minute for three minutes (McArdle et al. 1972; Chatterjee et al. 2004). One cycle entails stepping onto the top of the box, fully extending at the knees one foot at a time (up-up), and completed by returning to the ground one foot at a time (down-down). At the cessation of three minutes, heart rate was recorded after 15-seconds of recovery standing upright. Finally, participants completed general health and cricket history questionnaires.

During experimental sessions, participants completed two batting simulations (in a randomised order) separated by a minimum of one week and matched for time of day. Batters were also instructed to refrain from high-intensity physical activity for the 48-hours preceding testing. An indoor batting arena with an artificial playing surface ($L = 30$ meters, $W = 12$ meters) was used for conducting the batting simulations. Dry bulb temperature was recorded and averaged at 23°C and sessions were conducted between 09:00am and 16:00pm. An electric bowling machine (BritBowler, Winters Solutions, South Africa) was set at $110\text{km}\cdot\text{h}^{-1}$ to project deliveries with swing moving away from both left- and right-handed batters. Outcome measures obtained during experimental sessions are summarized in (Table 3.1).

TABLE 3.1: Summary of outcome measures, assessment periods and methodology during experimental sessions

Variable of Interest	Assessment Periods	Method/Instrument	(unit of measure)
Sweat Rate	Pre + Post Sim.	Calculated from change in mass, digital scale	(kg)
Energy Metabolism			
Blood [Lactate]	Cessation of phases, Pre + Post	Lancet + handheld lactate analyser	($\text{mmol}\cdot\text{L}^{-1}$)
Heart Rate	Cessation of every over	ECG chest strap + wristwatch	($\text{beats}\cdot\text{min}^{-1}$)
Muscular Output			
Peak Power	Pre + Post Sim.	Maximal vertical jump test + force mat	(Watts)
Sprint Time	Every delivery, when applicable	Timing gates spanning length of wicket	(sec)

On arrival at the batting arena, participants were fitted with a heart rate monitor and a resting blood lactate measurement was obtained. Thereafter, a cricket specific 10-minute warm-up was performed comprising of sub-maximal shuttles, dynamic lunges, skipping, and dynamic squats. Following the warm-up, the maximal jump test was performed. The Squat Jump (SJ) and Counter Movement Jump (CMJ) were performed

in alternating order until three measurements of each jump were obtained. A resting period of 1-minute was allowed between jump attempts. For the SJ, participants were instructed to reach 90° of flexion at the hip and knee, while a researcher stood at the participants profile to ensure the desired range of motion is reached. In this position, participants paused for 3 seconds before fully extending at the hip, knee and ankle. Similarly, for the CMJ, participants were instructed to reach 90° of flexion at the hip and knee however, once this position was reached participants immediately exert full extension at the hip and knee with no pause. Following the jump test, body mass was assessed with and without protective gear (pads, gloves, helmet). Once batters entered the batting arena they were familiarized with their requirements and the positions of scoring zones. An audiotape was used to inform the principal researcher and batter on the current over number, the run requirements within the over, and a buzzer cue for timing the release deliveries.

The PowerPlay phase commenced and upon the completion of every over heart rate was recorded. Sprint times were measured continuously when batters completed on-strike and off-strike shuttles. At the completion of the PowerPlay and Middle phase blood lactate was assessed, and participants were allowed to have a short comfort break to consume water to thirst. Water consumption was weighed and matched between experimental sessions by providing the measured amount on subsequent experimental sessions to be consumed fully. At the completion of the batting simulation participants provided a final blood lactate measurement, body mass with and without protective gear and a final maximal jump test was performed.

3.2.5 Twenty20 Batting Simulations

Two Twenty20 simulations were developed to simulate match play for an individual 'Low Strike Rate' and 'High Strike Rate' innings. To elucidate the effect of batting intensity (strike rate), both batting simulations were designed to produce an innings of equal duration by standardizing time at the crease and deliveries faced. The simulations were developed in two phases, described in detail by (Lopes et al. 2021). The High Strike Rate innings requires the batter to score 88 runs at a strike rate of 173. The Low Strike Rate innings simulates an innings of 61 runs at a strike rate of 120. Off-strike runs are identical in both innings, with 44 runs scored at a strike rate of 101 (Lopes et al. 2021).

The batting simulations were divided into three phases: PowerPlay, Middle and Close Innings. These phases allowed scoring zones to be manipulated as the simulation progressed providing a form of match realism. During the PowerPlay, four scoring

zones were available, and thereafter reduced to three zones. Batters were instructed that boundaries would only be rewarded if struck through a scoring zone. Further, batters were asked to perform shuttles at maximum intensity for the duration of the simulation. Singles were run from the striking crease and a full 180° turn was required at the opposite crease. Similarly, two's required two full shuttles and a full turn at the final crease and four's required one and a half shuttles. For off-strike deliveries batters were allowed to 'back-up' at the crease anticipating a run and running at the sound of the ball cue.

3.2.6 Data Analysis

Data was analysed using R version 3.2.2 (Team [2016](#)) and presented as mean (SD). It was determined that a sample of 34 batters would provide 80% power ($\beta = 0.2$) to detect a medium effect size ($d = 0.5$) difference in physical variables (peak power expected mean (SD) = 4000 (150)) at 5% significance level. A Shapiro-Wilk W test and qqnormal plots revealed that variables of interest were normally distributed. Peak power output was determined from the mean of three trials of each jump type (CMJ + SJ) independently. Statistical significance thresholds were set at $p < 0.05$. Peak power output and change in body mass were assessed using a paired t-test within each simulation and a repeated measures ANOVA for interaction between simulations, thus these variables are analysed between simulations from batters who completed all experimental sessions. Blood lactate concentration, sprint times and heart rates were assessed using linear mixed effects models and the lme4 package (Bates et al. [2007](#)). Phase (measurement periods) and simulation (Low vs High strike rate innings) were fixed effects. Subjects/batters were fitted random intercepts and slopes. Mixed effects models do not assume sphericity and allow unbalanced sample groups to be compared across fixed factors, thus these variables could use all available data. Residual plots were visually inspected for obvious deviations of homoscedasticity or normality. P-values were obtained from likelihood ratio tests with Bonferroni adjustment.

3.3 Results

Anthropometric variables and cricketing history of ($n = 14$) experienced batters are presented in (Table [3.2](#)). Due to injury or unavailability, 10 participants completed both simulations. While 11 subjects performed the low strike rate innings and 13 performed the high strike rate innings.

TABLE 3.2: Anthropometric and physiological measurements of top-order batters and their cricketing history (n=14)

	Mean (SD)	Range
Age (yrs)	22.3 (3.4)	19–30
Lean Body Mass [*] (kg)	70.78 (8.82)	59.20–89.31
Aerobic Capacity [†] (ml·min ⁻¹ ·kg ⁻¹)	52.56 (4.45)	44.94–57.12
Stature (cm)	178 (8)	169–189
Competitive Playing Experience (yrs)	15 (4)	9–20
Private Coaching Experience (yrs)	6 (2)	1–10

^{*} Lean body mass measured from sum of seven skin folds (Jackson & Pollock, 1985)

[†] Maximum aerobic capacity assessed from heart rate recovery to a constant workload Queens College step-test (McArdle et al., 1972, Chatterjee et al., 2004)

3.3.1 Peak Power Output

There were contrasting changes to peak power output in response to either simulation. In the low strike rate simulation, a mean decrease of 228.3 (602.3) watts was observed post simulation across both jump methods (CMJ + SJ) (Table 4) however the pre and post differences for both measurements (CMJ and SJ) were not significantly different. Conversely, the high strike rate innings produced a mean increase of 167.0 (575.3) watts (Table 3.3). Eccentric Utilization Ratios (EUR) were not affected following the low strike rate innings (1.01 (0.03) vs 1.02 (0.04), $p = 0.69$) or the high strike rate innings (1.01 (0.03) vs 1.01 (0.04), $p = 0.90$). Finally, there was no interaction between simulations and peak power measures in the CMJ ($f(1,9) = 3.8$, $p = 0.08$) and SJ ($f(1,9) = 3.3$, $p = 0.08$).

3.3.2 Change in Mass

Participants experienced a decrease in body mass following both simulations (Table 3.3). In the low strike rate innings, participants lost an average of 0.6kg or 0.7 (0.1)% of their starting body mass while the high strike rate innings produced a loss of 1 (0.2)%. There was no interaction between simulations and weight measurement periods $f(1,9) = 0.15$, $p = 0.71$ with or without kit $f(1,9) = 0.83$, $p = 0.39$.

TABLE 3.3: Changes in lower-limb peak power output and body mass in response to two Twenty20 batting simulations performed by experienced batters

	‘Low’ Strike Rate (n = 11)				‘High’ Strike Rate (n = 13)			
	Pre Mean (SD)	Post Mean (SD)	Δ [95% Conf. Int]	p-value	Pre Mean (SD)	Post Mean (SD)	Δ [95% Conf. Int]	p-value
Peak Power (Watts)								
SJ *	4277.6 (399.2)	4043.7 (609.6)	-233.9 [-172.5 640.0]	0.23	3974.6 (586.2)	4147.0 (674.6)	174.2 [-543.0 205.2]	0.34
CMJ †	4319.7 (386.8)	4096.9 (581.7)	-222.8 [-199.9 645.6]	0.27	4032.1 (625.1)	4208.1 (730.5)	176.0 [-538.5 208.2]	0.35
Mass (kg)								
w/ kit	88.8 (17.5)	88.2 (17.5)	0.6 [0.4 0.8]	<0.001	89.5 (16.5)	88.9 (16.4)	0.6 [0.3 0.7]	<0.001
w/o kit	85.1 (17.8)	84.5 (17.6)	0.6 [0.4 0.9]	<0.001	85.7 (15.9)	84.8 (15.7)	0.9 [0.7 1.0]	<0.001

Data represent peak power outputs derived from two maximal vertical jump techniques assessed with three repetitions of each technique for averaging. Mass was recorded immediately prior and upon completion of either simulation

* Squat Jump

† Counter Movement Jump

Δ Change (Post - Pre)

3.3.3 Blood Lactate

Blood lactate concentrations were different across measurement periods of a simulation $f(3,38) = 15.54$, $p < 0.001$, $\eta_p^2 = 0.52$ (Figure 3.1). Pairwise post-hoc analyses of measurement periods confirmed that compared to pre-simulation measurements, lactate concentration was greater in all remaining measurement periods ($p < 0.001$) with no differences between remaining period combinations $f(3,37) = 2.38$, $p = 0.09$, $\eta_p^2 = 0.16$. Overall, both simulations induced similar concentrations of blood lactate $f(1,12) = 0.17$, $p = 0.67$, $\eta_p^2 = 0.01$.

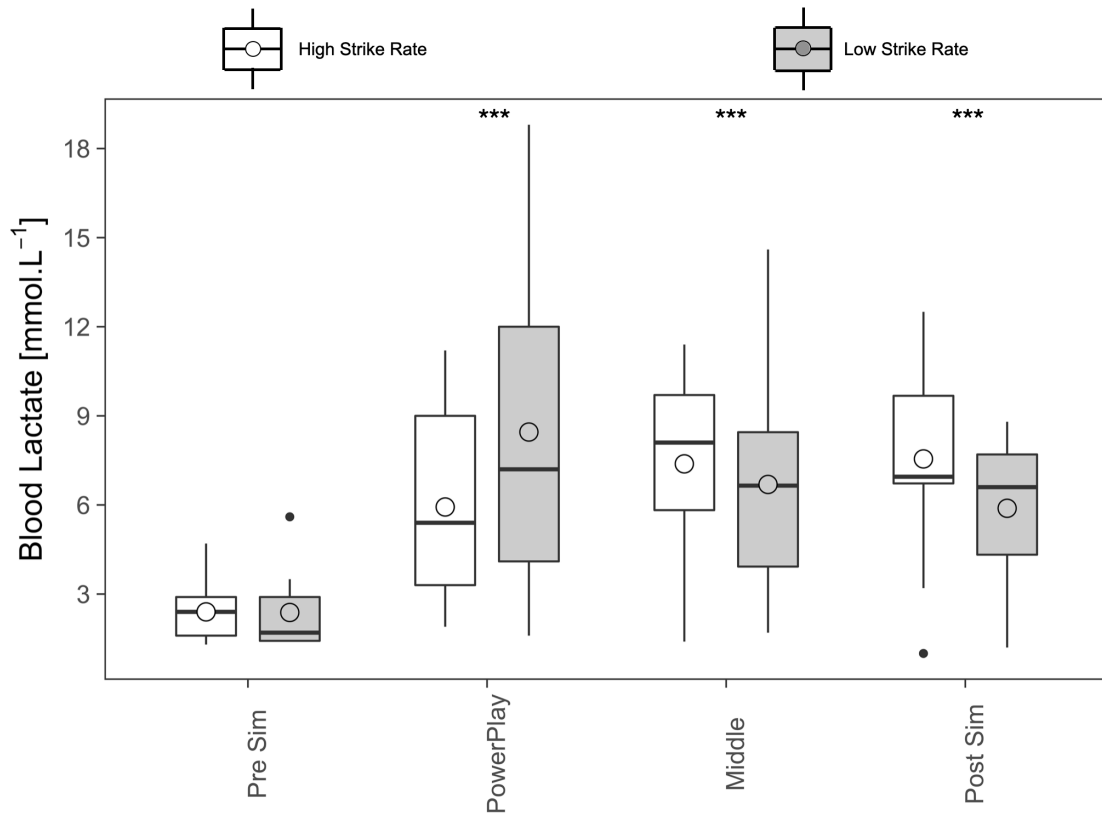


FIGURE 3.1: Blood lactate concentration measured at equal intervals of experienced cricket batters ($n=14$) in two Twenty20 batting simulations. Open circles indicate mean values, closed circles represent outliers. *** $p < 0.001$ different to pre-simulation measure, pairwise comparison with Bonferroni adjustment

3.3.4 Heart Rate

Heart rate responses of both simulations were considerable, with the low strike rate simulation producing a least squares mean (SE): $148 (2.6) \text{ beats} \cdot \text{min}^{-1}$ and the high strike rate simulation: $153 (2.8) \text{ beats} \cdot \text{min}^{-1}$. Overall, heart rate was higher in the high strike rate innings by $\beta = 5.4 \text{ beats} \cdot \text{min}^{-1}$ ($\text{SE} = 4.3$), $p < 0.01$ (upperCL = 10.8,

lowerCL = 0.45) (Figure 3.3). In both simulations, the Middle and Close Inn. phases produced higher heart rates compared to the PowerPlay (Table 3.4).

TABLE 3.4: Heart rate responses across phases of two Twenty20 batting simulations

Phase	‘Low’ Strike Rate			‘High’ Strike Rate		
	Mean (SE)	Lower CL.	Upper CL.	Mean (SE)	Lower CL.	Upper CL.
PowerPlay	131 (4.1) [#]	120	143	138 (4.4) [*]	126	150
Middle	159 (4.1) ^a	147	170	161 (4.4) ^{a†}	149	173
Close Inn.	155 (4.2) ^a	143	166	162 (4.4) ^a	150	174

Data represent least squares mean and standard error of innings phases with 95% lower and upper confidence limits.

Within a simulation – $p < 0.01$ ^aPowerPlay

Between simulations – $p < 0.01$ [†]PowerPlay ; ^{*}Middle ; [#]Close Inn.

3.3.5 Sprint Times

In the high strike rate simulation, on-strike sprint times were slower overall by $\beta = 0.10$ (SE = 0.03) seconds ($p < 0.01$ (upper C.L = 0.15, lower C.L = 0.05)) compared to the low strike rate variant. Similarly, off-strike sprint times were slower by $\beta = 0.05$ (SE = 0.02) seconds compared to the low strike rate innings ($p < 0.01$ (upperCL = 0.09, lowerCL = 0.01)). Although sprint times were faster in the low strike rate simulation, there was greater deterioration to sprint performance as the simulation progressed (Figure 3.2). On-strike sprint times increased by $\beta = 0.02$ seconds (SE = 0.005, $p < 0.01$) per over in the low strike rate innings while less deterioration per over was seen in the high strike rate innings $\beta = 0.005$ seconds (SE = 0.003, $p = 0.086$). However, a similar deterioration to off-strike sprint times was observed in both innings. In the low strike rate innings, off-strike sprint times increased by $\beta = 0.007$ seconds (SE = 0.002, $p < 0.01$) per over and $\beta = 0.006$ seconds (SE = 0.002, $p < 0.01$) per over in the high strike rate innings.

3.4 Discussion

Few studies have examined the physiological stress of Twenty20 cricket and, in particular, the exertion of prolonged batting. In a holistic investigation of individual innings’, two hour-long Twenty20 simulations produced considerable physical stress in experienced, top order batters. The run scoring intensity (strike rate) of an innings was found to have little effect on sweat rate, peak power output and blood lactate accumulation. However, the high strike rate simulation induced higher heart rates and slower

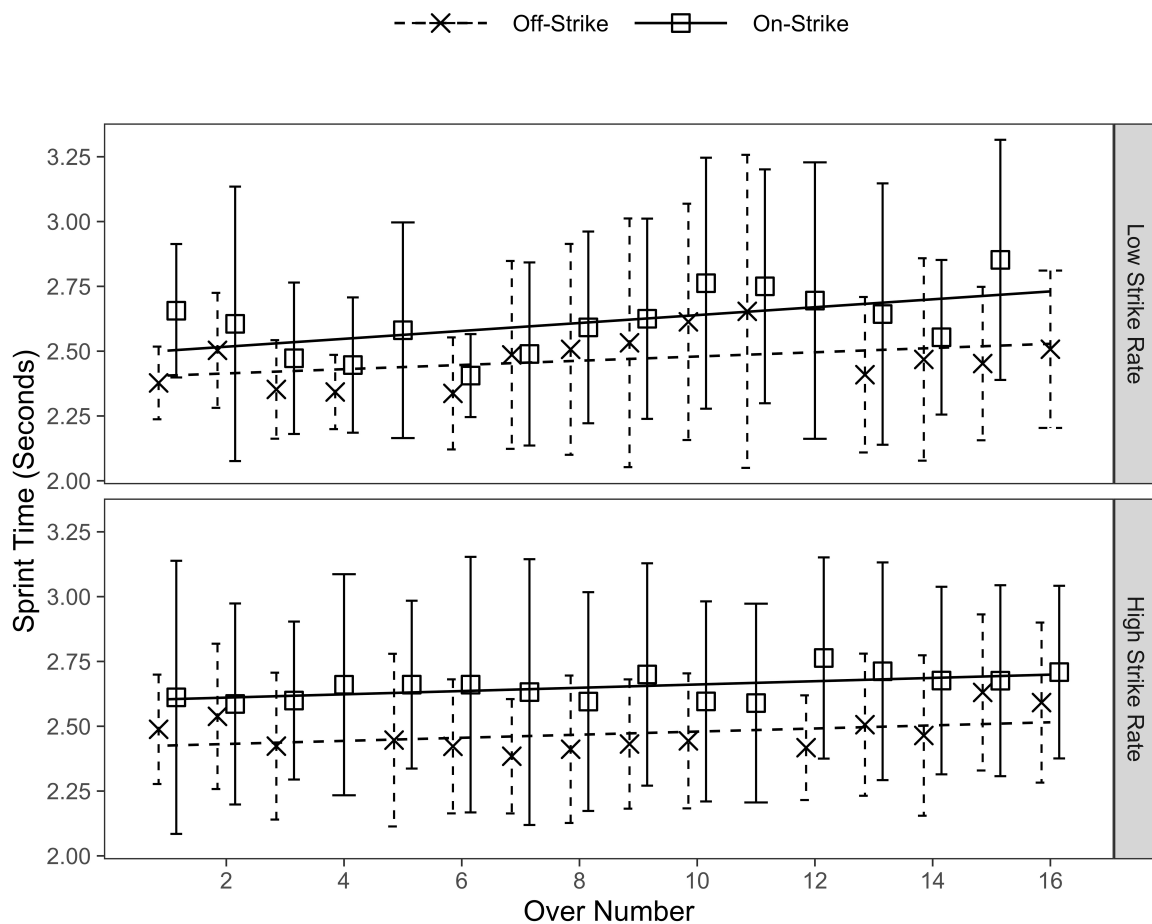


FIGURE 3.2: Sprint times of on-strike and off-strike runs scored by experienced cricket batters ($n=14$) in two T20 batting simulations. Reported as mean and standard deviation with overlaid linear model $y \sim x$

sprint times compared to the low strike rate innings. These findings suggest batting in Twenty20 cricket is physically demanding but, strike rate can augment the stress imposed on the batter in innings of similar duration.

In our study, sweat rate was similar in both high and low strike rate variants with participants experiencing a mass loss of 1.0 (0.2)% and 0.7 (0.1)% respectively. Gamage et al. (2016) documented a similar change in mass ($0.9 \pm 0.5\%$) following a two-hour training session with no fluid restrictions. Importantly, the authors observed that a decrease in mass greater than 1% significantly impacted batting sprint performance (Gamage et al. 2016). Although our study allowed water intake ad libitum (but matched between sessions), batters still approached the 1% threshold following either innings. Further, research has identified that extreme climate will have a negative effect on fluid loss of batters (Gore et al. 1993). The moderate temperature (23°C) in our controlled, indoor

study combined with the thermogenic effect of protective equipment (King, Christie, and Todd [2002](#)) may have caused sufficient dehydration to impair performance but, our results may represent the minimum expected loss thus not causing significant declines in performance.

Deficits to muscle function were also observed in sprint performance but less conclusively in peak power output. In the low strike rate innings, on-strike sprint times deteriorated by 0.32 seconds (12.8%, $p < 0.01$) in the final overs of the simulation. Off-strike sprint times were less affected, producing a small deficit of 0.12 seconds (4.7%, $p < 0.01$) in the final overs (Figure [3.2](#)). Conversely, in the high strike rate innings on-strike sprint times were not adversely affected (deterioration of < 0.1 seconds, $p = 0.086$) but off-strike sprint times were slower by a tenth of a second (4%, $p < 0.01$). Although more deterioration was observed in the low strike rate innings, the high strike rate innings produced slower on-strike (2.64 (0.40) seconds vs 2.55 (0.43) seconds, $p < 0.01$) and off-strike sprint times (2.47 (0.28) seconds vs 2.42 (0.34) seconds, $p < 0.01$). The slower sprint performance observed in the high strike rate innings may be attributed to the stroke selection of batters in this simulation. To meet the requirements of the high strike rate simulation more boundaries are scored which inadvertently leads batters to prioritise bat speed to impart greater impact velocity on deliveries (Peploe et al. [2019](#)). In doing so, batters may complete strokes in unfavourable postures to set off for quick shuttles, thus negatively impacting sprint times (Callaghan et al. [2015](#)). Reduced sprint performance may adversely affect a batters ability to achieve competitive run totals and increase risk of dismissal by 'run-out'. Elite batters have been found to exhibit pacing strategies (Christie et al. [2018](#)) in an attempt to preserve sprint performance. An alternative explanation for slower sprint times observed in the high strike rate innings may be a result of batters employing pacing strategies especially when perceived run scoring pressure is eased by striking boundaries early in the innings.

Previous studies have documented a decrease in muscular output induced by high intensity shuttle running (Noakes and Durandt [2000](#); Highton, Twist, and Eston [2009](#)). More pertinently, the eccentric strength of knee-flexors appear most affected (Christie et al. [2019](#)) which may predispose athletes to injury (Aagaard et al. [1998](#); Christie et al. [2019](#)). However, peak power output and eccentric utilization ratio (EUR), assessed by vertical jump performance, appear to be maintained in our study. In fact, the high and low strike rate innings produced contrasting changes to peak power output (Table [3.3](#)). Further, EUR which provides insight to lower-limb eccentric performance and neuromuscular function (Young [1995](#); McGuigan et al. [2006](#)) did not change following either simulation. Typically, an EUR greater than one and preserved following strenuous

eccentric contractions indicates subjects maintained appropriate stretch-shortening-cycles which may be negatively affected by fatigue (Komi [2000]; McGuigan et al. [2006]). Thus, in our study batters appear well acclimatized to the strength requirements of an intense batting innings. However, a more informed conclusion would require additional jump performance measurements up to 48-hours after an innings to account for biphasic recovery highlighted in previous studies (Komi [2000]).

The metabolic cost of Twenty20 batting appears to be the most affected by strike rate. Heart rates in both batting simulations were consistent with findings of Petersen et al. ([2010]) recorded during second-tier international fixtures. In the competitive Twenty20 innings, mean heart rates of 149 ± 17 beats $\cdot$ min $^{-1}$ were observed (Petersen et al. [2010]) while our simulated low strike rate innings produced heart rate mean 148 ± 21.9 beats $\cdot$ min $^{-1}$ and the high strike rate innings: 153 ± 21.1 beats $\cdot$ min $^{-1}$ (Figure 3.3). Further, the high strike rate innings produced greater heart rates throughout the simulation ($\beta = 5.4$ beats $\cdot$ min $^{-1}$, $p < 0.01$). Although heart rate increased with innings progression, both innings produced similar mean heart rates in the latter phases, contrary to ODI simulations where highest heart rates are observed in the final phases with undulations in preceding periods (Houghton et al. [2011]; Houghton, Dawson, and Rubenson [2011]). Evidently, the movement patterns of Twenty20 cricket are unique (Petersen et al. [2010]) and a batting innings appears to have no breaks in intensity resulting in sustained demands.

A direct measure of anaerobic metabolism confirms the assumption of sustained metabolic demand. Blood lactate concentration increased with innings progression and higher average concentrations were observed in the high strike rate innings, particularly in the latter phases. Contributions of anaerobic glycolysis therefore remained throughout the simulations which may indicate that a Twenty20 innings allows little respite of intensity as seen in other formats (Petersen et al. [2010]; Houghton, Dawson, and Rubenson [2011]). The low strike rate innings produced blood lactate concentrations similar to BATEX and Battlezone protocols (Houghton et al. [2011]; Vickery et al. [2013]). Across stages of BATEX, Houghton, Dawson, and Rubenson ([2011]) reported blood lactate concentrations of $3.2 - 4.5$ mmol $\cdot$ L $^{-1}$ while the low strike rate innings ranged from $\beta = 2.8 - 4.4$ mmol $\cdot$ L $^{-1}$. However, in the Middle and Close Innings phases of the high strike rate innings, blood lactate concentrations ($\beta = 5.1$ and 5.2 mmol $\cdot$ L $^{-1}$ respectively; Figure 3.1) exceeded previous studies (Houghton, Dawson, and Rubenson [2011]; Vickery et al. [2013]; Vickery, Dascombe, and Duffield [2014]). Interestingly, the high and low strike rate innings require an equal number of on-strike shuttles across the Middle and Close Innings phases (29.5 shuttles). Although the high strike rate innings requires

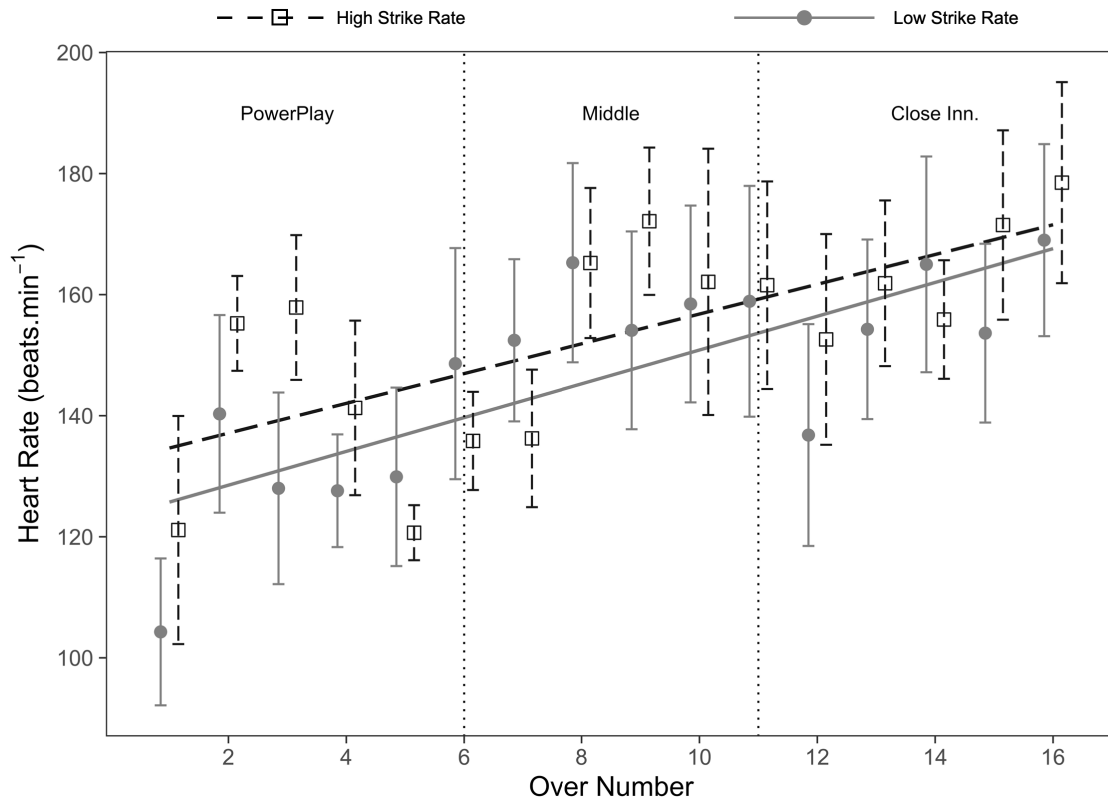


FIGURE 3.3: Heart rate responses of experienced cricket batters ($n=14$) during two Twenty20 batting simulations. Reported as mean and standard deviation with overlaid linear model $y \sim x$

more runs (66 vs 49 runs) scored mostly from boundaries (9 vs 5). Considering the running demand is similar between simulations, the batting effort necessary to seek boundaries appears to increase the load on the athlete.

Limitations Batting simulations provide a comparable dose of physical stress but, the design of this study presents other limitations. Deliveries were projected from a bowling machine, with little variation. Thus, batters may not experience comparable batting fatigue due to the low variety of responding strokes. Another critique of batting simulations with run-scoring dictation is that batters are told how many runs to score at the beginning of an over. Batters can therefore prepare and distribute physical efforts strategically but, a competitive match does not provide this opportunity.

Conclusion and Future Research Direction Our results demonstrate that Twenty20 batting produces a similar physical load compared to longer game formats studied previously. However, strike rate may increase the workload placed on the athlete resulting

in slower sprint times and higher metabolic stress (aerobic and anaerobic). Future research should continue to develop an understanding of factors which influence batting related fatigue. Further, as Twenty20 fixtures often accumulate within short periods in tournaments the cumulative load experienced by athletes is also of interest. Our study was limited to a single assessment with a minimum of seven days' rest between simulations. Therefore, follow-up assessments on days immediately succeeding a Twenty20 innings may provide a more holistic understanding of the stress of batting and inform recovery strategies for athletes.

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Disclosure statement

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Chapter 4

Cognitive and Perceptual Strain of Twenty20 Batting - Phase 2

Few studies have investigated the workload of batting in Twenty20 cricket and data describing the cognitive strain of batting is particularly sparse. Chapter IV is among the first to bridge this gap. Results presented in chapter III suggest that run scoring rates have some influence on the physical workload of batting. Although, differences in physical strain are not large enough to implicate fitness as a primary deterrent of batting performance when striking rates are increased. Thus, the holistic interpretation of cognitive and physical strain is pertinent to understanding factors of batting performance.

Contribution of Authors;

T Lopes - conceptual design, data collection and analysis, data visualisations and writing

D Goble - conceptual design, supervision

S Kerr - supervision, proof-reading and editing

B Olivier - supervision, proof-reading and editing

The cognitive fatigue experienced by batters is modulated by the strike rate of a Twenty20 innings

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Abstract

An individual Twenty20 batting innings requires prolonged cognitive control which may be influenced by the high physical intensity of run scoring. How batters perform through the exercise-cognition interaction is unknown and this study aimed to elucidate the impact of run scoring intensity (strike rate) on the cognitive efficiencies of skilled, amateur batters. Two innings simulations were investigated in a randomised cross-over design in fourteen batters (mean $\pm$ SD: age 22.3 $\pm$ 3.4 years; batting experience 15 $\pm$ 4 years). The high strike rate innings was perceived as marginally more strenuous to lower-limb musculature ($\beta = 0.6$, $p = 0.049$), although cardiovascular exertion was comparable to the low strike rate innings ($\beta = -0.3$, $p = 0.432$). Batters produced increased error-rates in executive functioning following high strike rate batting ($r = 0.60$, $p = 0.05$), and prefrontal cortex haemodynamics reveal increased concentrations of deoxygenated haemoglobin in the right dorsolateral pre-frontal cortex. The low strike rate innings resulted in smaller reductions to working memory response times ($d = 0.76$, $p = 0.03$ vs $d = 1.20$, $p < 0.01$), but executive functioning performance appears preserved ($d = 0.08$, $p = 0.84$) and oxygenated haemoglobin concentration is increased compared to the high strike rate innings. The cognitive exertion of a Twenty20 innings appears to be moderated by run scoring intensity. Batters should be routinely exposed to the combined mental and physical stressors of an innings to aid skill development.

Keywords: batting, cognition, hypofrontality, psychomotor function

4.1 Introduction

The successful interception of a high-velocity cricket ball requires a multi-joint motor behaviour to be co-ordinated and executed within millisecond temporal constraints (Scanlan et al. 2016). The neurological mechanisms of batting could be pragmatically described by the synaptic relay of visual stimuli to the visual and somatosensory cortex (Rolfs and Schweitzer 2022), followed by hierarchical inputs of the premotor and motor cortex, basal ganglia, cerebellum, nuclei of the brain stem and lower motor neurons, eliciting the muscular contractions of stroke play (Fuster 2017; Rolfs and Schweitzer 2022). However, the prefrontal cortex enables the key integration of sensory input and executive control of movement to modify memorized motor patterns with high spatial and temporal accuracy (Fuster 2013). In other words, the neural basis of batting skill is the organizational, goal-directed cognitive ability of the prefrontal cortex. A batter's ability to consistently intercept deliveries, despite attempts of deception and variation from opposing bowlers, requires prolonged cognitive acuity which is yet to be fully studied.

The objective of a cricket match is to score more 'runs' than the opposing team. Batters compete against opposing bowlers in separate innings to achieve competitive run totals. Ultimately, run scoring is the result of a series of decisions directing movement (motor cognition) from the evaluation of ball-motion and other match stimuli (Scanlan et al. 2016). A mechanism of prioritizing information for central processing (attention) concentrates limited neural resources on the most pertinent match stimuli (Corbetta and Shulman 2002; Chun, Golomb, and Turk-Browne 2011). Here the frontoparietal network of the prefrontal cortex enables goal-directed ('top-down') attention and supplements motor control of the eye to maintain gaze on the bowling arm and ball-flight (Corbetta and Shulman 2002; Gazzaley and Nobre 2012; Ptak 2012). The batter has 450–600ms from ball release till the delivery is within striking range (McLeod, Jenkins, et al. 1991; Land and McLeod 2000). For optimal interception, ball-contact should be made when bat-speed reaches peak velocity (Peploe et al. 2019) – a window of 2–5ms (McLeod, Jenkins, et al. 1991; Tresilian 2005). Selective visual attention alleviates these temporal constraints by preparing relevant neural networks, enhancing efficiency, and minimizing the delay of decision making/action (Sabine and Leslie 2000; Chun, Golomb, and Turk-Browne 2011). But inherent visual-motor delay means erroneous decisions may remain uncorrected (Tresilian 2005; Sarpeshkar and Mann 2011), leaving the batter at risk of being 'dismissed'. Therefore, skilled batters begin the perception-action cycle by anticipating delivery characteristics before ball-release (Müller, Abernethy, and Farrow 2006; Sarpeshkar and Mann 2011).

Studies have shown that skilled batters accurately predict upcoming deviations to ball-flight trajectory from kinematic variables in the bowling action (Müller, Abernethy, and Farrow [2006]; Weissensteiner et al. [2008]). To achieve this, neural representations of the present kinematic action and corresponding instances in long-term memory need to be readily available for central processing i.e., within the focus of attention (Sabine and Leslie [2000]; Gazzaley and Nobre [2012]). Working memory is the overlapping function of attention which maintains goal-relevant information in an active state (Baddeley [2012]; Oberauer [2019]) and biases which stimuli enter the focus of attention in upcoming/latter phases of the delivery (Gazzaley and Nobre [2012]; Miller, Lundqvist, and Bastos [2018]). That is, working memory serves to pre-select a subset of motor responses which correspond to the availing kinematic cues in the bowling action (Eriksson et al. [2015]; Furley and Wood [2016]). Second, manipulation of the working memory enables the batters motor response to reflect where the delivery might be in time and subsequently directs the reallocation of attentional resources towards processing the adequacy of the motor response with anticipated novel stimuli in ball-flight (Furley and Wood [2016]; Miller, Lundqvist, and Bastos [2018]). Evidently, after ball-release the central vision of a skilled batter quickly saccades to the predicted location of bounce (Land and McLeod [2000]), while the forward stride (lower-limb motor response) initiates immediately after ball-release, but stride length is modified depending on the location of bounce (Thomlinson [2009]; Sarpeshkar and Mann [2011]). Thus, working memory describes the ‘visuospatial sketchpad’ of stroke production to anticipate ball-motion and adequately plan the stages of motor response (Baddeley [2012]; Miller, Lundqvist, and Bastos [2018]).

In a similar manner, working memory influences the perception and action of batters from match stimuli gathered throughout an innings. Contextual information of the field of play (fielding positions) are maintained and updated when relevant. This neural representation of the field provides targets for placing intercepted deliveries, thus guiding executive motor control (Yarrow, Brown, and Krakauer [2009]; Furley and Wood [2016]). The maintenance and manipulation of the working memory also provides the interface for cognitive evaluations (Baddeley [2012]; Miller, Lundqvist, and Bastos [2018]) of tactical game management. For example, changes made to the field inform tactical strategies of the opposing team. The batter must reassess the risk-reward ratio of different strokes, consider opportune moments to attack or rather bide time to wait for further bowling and fielding changes. Hence, another factor of batting performance is longer-term, tactical planning (executive functioning) towards the goal of maximising runs (Yarrow, Brown, and Krakauer [2009]; Furley, Schweizer, and Bertrams [2015]).

Little is known about the resilience of a batters' cognitive function to the stress of prolonged batting. The sustained cognitive load of an innings may induce fatigue which negatively affects muscular performance (Marcora, Staiano, and Manning [2009]; Van Cutsem et al. [2017]). While the high-intensity physical stress of run scoring (Pote and Christie [2014]) produces contrasting acute changes to cognitive functioning (Loprinzi [2018]; Mehren et al. [2019]). Finally, the psychological stressors of perceived physical exertion (Zering et al. [2017]), performance anxiety and crowd dynamics (Nieuwenhuys and Oudejans [2017]) compound the cognitive load of an innings, adding another influence on the batter's ability to effectively score runs. Therefore, to accurately assess cognitive function in response to prolonged batting, multiple factors of ball-striking, shuttle running, and match pressure should be replicated. Using a simulated individual batting innings which models scoring 100 runs in the One Day International (50 over) format, Goble and Christie ([2017]) demonstrated that batting duration and associated fatigue negatively impacts properties of cognition. Namely, visual attention and executive functioning deteriorated with innings progression (Goble and Christie [2017]). Above innings duration and total accumulated runs, the rate of run scoring ('strike rate') is equally crucial to batting performance. Even more so in Twenty20 cricket where the number of overs in a team innings is limited to 20 (120 deliveries) meaning striking rates are imperative to achieving competitive run totals. To our knowledge, no study has investigated the cognitive costs of batting at different strike rates. Therefore, the purpose of this study was to assess changes to prefrontal cortex resource allocation/utilization and parameters of cognitive performance in response to two Twenty20 batting simulations which mimic a high and low strike rate innings.

4.2 Methods and Materials

4.2.1 Participants

We recruited fourteen ($n = 14$) experienced (>6 years competitive playing experience), skilled batters (represented at national or domestic level). Participants were required to be free from injury in the 6-months prior to the study and currently competing in a competitive (amateur or semi-professional) league. The investigation was conducted during a competitive season to ensure batters were match fit. Upon recruitment participants signed informed consent and completed health surveys. All procedures were reviewed by the Human Research Ethics Committee (clearance no: M180872).

4.2.2 Experimental Design and Procedures

This study implemented a cross-sectional, repeated measures laboratory design comprising of one introductory and two experimental (batting) sessions. In the introductory session, participants were accustomed to the CogState test battery and instructed of their requirements in the following experimental sessions. Anthropometry was collected as well as a maximum aerobic capacity test. Finally, participants completed general health and cricket history questionnaires.

During experimental sessions, participants completed two batting simulations (in a randomised order) separated by a minimum of one week and matched for time of day. Batters were also instructed to refrain from high-intensity physical activity for the 48-hours preceding testing. The order of experimental sessions were randomly assigned and batters were aware that both sessions would be of equal length but otherwise blinded to the differences between simulations and objectives of the study. An indoor batting arena with an artificial playing surface ($L = 30$ meters, $W = 12$ meters) was used for conducting the batting simulations. Dry bulb temperature was recorded and averaged at 23°C and sessions were conducted between 09:00am and 16:00pm. An electric bowling machine (BritBowler, Winters Solutions Ltd., South Africa) was set at $110\text{ km}\cdot\text{h}^{-1}$ to project deliveries with ‘swing’ moving away from both left and right-handed batters. An audiotape was used to inform the principal researcher and batter of the current over number, the run requirements within the over, and a buzzer cue for timing the release deliveries.

Cognitive function was assessed before and after completion of the batting simulations by measuring prefrontal cortex haemodynamics during the CogState test battery. Participants arrived and were directed to a quiet area to complete the cognitive assessment. Thereafter, a cricket specific, 10-minute warm-up was performed comprising of sub-maximal shuttles, dynamic lunges, skipping, and dynamic squats (Andrade et al. 2015). Participants were then allowed to perform self-selected stretches and prepare to begin the batting simulation. Entering the batting arena, batters were re-familiarised with their requirements and the position of scoring zones. The PowerPlay phase commenced initiating the batting simulation. At the cessation of every over psychophysical variables were verbally documented. Batters were allowed a comfort break to consume water at the end of phases. Water consumption was weighed and matched between experimental sessions by providing the measured amount on subsequent experimental sessions to drink fully. At the completion of the batting simulation, batters exited the arena towards the cognitive function testing station to complete the final CogState battery.

4.2.3 Twenty20 Batting Simulations

The development and implementation of the batting simulations is described by Lopes et al. (2021). The high and low strike rate simulation were matched for duration, number of on-strike deliveries, number of off-strike deliveries and run requirements from off-strike deliveries. For on-strike deliveries, the high strike rate innings requires the batter to achieve a strike rate of 173, including 13 boundaries. The low strike rate innings requires the batter to achieve a strike rate of 120 with 7 boundaries. Both simulations therefore are a total of 93 on-strike and off-strike deliveries for an innings duration of 1 hr and 2 min.

4.2.4 Anthropometry and Cricket History

Stature and mass were recorded to the nearest 0.1kg and 0.5cm respectively using a digital scale (Elektra, Bolzano, Italy) and meter stick.

4.2.5 CogState Test Battery

The CogState (Melbourne, Australia) test battery is a scientifically validated computer-based task used to assess cognitive functioning and impairment (Maruff et al. 2009). The computerized test battery was chosen based on its test-retest reliability and limited improvements in task performance due to practice effects (Falleti et al. 2006). Further, to minimize the effects of improved task performance associated with practice effects, participants performed three baseline assessments (i.e. three complete rounds) of each cognitive test as described by (Falleti et al. 2006) during the introductory session. The test battery comprised of three consecutive tasks which assessed executive function, visual attention and working memory. The test battery was performed in a quiet area on site, to ensure participants were not distracted. Executive function was assessed using the Groton maze learning task (Pietrzak et al. 2008). In this task, participants were required to learn a maze quickly and accurately in the least possible number of moves. Total number of errors and response accuracy were the outcomes of interest from the maze task (Pietrzak et al. 2008). To assess working memory the N-back task as described by Ayaz et al. (2012) was performed. A single randomised card was displayed in cycles, and participants were required to recall if the card currently displayed matched the card for suit and colour seen one or two cycles back (one-back, two-back). The one-back test was performed first followed by two-back. For the duration of the CogState test battery, the haemodynamic responses of the prefrontal cortex were measured using functional near infrared spectroscopy as described by (Ferrari and Quaresima 2012) (BIOPAC Systems Inc., USA).

4.2.6 Functional Near Infrared Spectroscopy (fNIR)

Prefrontal cortex haemodynamics were assessed during the CogState test battery. A secondary laptop and fNIR system (BIOPAC Systems Inc., USA) provided a non-invasive method of imaging the cortex. A headband with 18 infrared optodes was placed on the forehead which measured concentrations of oxygenated (HBO) and de-oxygenated (HBR) haemoglobin at a sampling frequency of 120 Hz. The headband was placed on the athlete's forehead and wrapped with crape bandaging to reduce ambient light interference. Raw signal was monitored in fNIR Studio v1.1 (BIOPAC Systems Inc., USA) and optode gain was adjusted to produce signal outputs between 800-1600mV. The athlete was then instructed to view a blank screen and the recording was initialized, beginning with a 3-seconds baseline measure. Markers were manually placed in the data during the CogState battery corresponding to individual test periods of the CogState battery. The raw signal was saved and processed using fNIR light software v1.4 (BIOPAC Systems Inc., USA) and modified beer-lambert law. Data processing was performed by applying an ambient light correction, high-pass frequency and smooth motion artifact filters respectively. Thereafter, markers within the data were used to extract segments of the test battery and a mean for each task was calculated (Groton-maze, one-back, two-back).

4.2.7 Psychophysical variables (Rating of Perceived Exertion)

Central (cardiovascular) and local (lower-limb) ratings of perceived exertion (RPE) were recorded at the cessation of every over. Batters were asked to verbally state their perceived exertion on the Borg scale (Borg [1982](#)) following the final delivery of every over. According to the scale, a score of six indicates the exertion of rest up to a maximum score of twenty, which indicates a no longer tolerable level of exertion i.e., a point of failure (Borg [1982](#)).

4.2.8 Data Analysis

Data was analysed using R version 3.2.2 (Team [2021](#)). Normality was confirmed using qq-normal plots and a Shapiro-Wilk test for each variable. The primary outcome measure for the Groton Maze task was total errors, and speed, determined from mean of the log10- transformed correct response times was a secondary outcome variable (Pietrzak et al. [2008](#)). For the n-back task, response time was the primary outcome variable and accuracy, determined from number of correct responses divided by the total number of responses was the secondary outcome variable (Maruff et al. [2009](#)).

Change in primary and secondary outcome measures were assessed using a paired t-test and nonparametric equivalent (Wilcoxon sign rank test) with significance set as $p < 0.05$. It was determined that to detect a medium effect size ($d = 0.5$) difference in response times (expected mean (SD) = 250 (45)), a sample of 31 batters would provide 80% power ($\beta = 0.2$) at 5% significance level. Cohen's d effect sizes estimated the magnitude of change between measures for parametric variables and an r conversion of z-scores for non-parametric variables (Pautz, Olivier, and Steyn 2018). Effect sizes were interpreted as small = 0 – 0.49; moderate = 0.5 – 0.79; or large ≥ 0.8 (Pautz, Olivier, and Steyn 2018). Psychophysical variables (local and central RPE) were assessed using linear mixed-effects models. Mixed models were fitted with simulation variants and their phases (time points) as fixed factors, while subjects/batters were allowed random intercepts and slopes. Significance was set to $\alpha = 0.05$.

4.3 Results

4.3.1 Participants

Fourteen ($n = 14$) batters with a mean of 15 (SD = 4) years competitive playing experience, aged 22.3 (3.4) years old, statured 178 (8) cm and mass of 82.3 (13.3) kg were recruited. Batters were free from injury and currently competing in amateur or semi-professional leagues in the top 7 of the batting order. Due to unavailability or injuries sustained in the period of the study, ten ($n = 10$) batters completed both simulations while eleven ($n = 11$) batters completed the low strike rate innings and twelve ($n = 12$) in the high strike rate variant.

TABLE 4.1: Cognitive performance measures from three CogState tasks in response to T20 batting simulations

	'low' strike rate ($n = 11$)				'high' strike rate ($n = 12$)			
	Pre Mean (SD/IQR [#])	Post Mean (SD/IQR [#])	p-value	ES ⁺	Pre Mean (SD/IQR [#])	Post Mean (SD/IQR [#])	p-value	ES ⁺
Groton Maze								
Errors [#]	33.8 (12.5)	37.9 (14.0)	0.84	0.08	35.8 (13.2)	41.5 (11.0)	0.05	0.60
Speed	0.93 (0.14)	0.97 (0.17)	0.52	0.20	0.99 (0.15)	1.00 (0.15)	0.80	0.08
One-Back								
Response Time	2.90 (0.08)	2.86 (0.08)	0.03	0.76	2.90 (0.07)	2.83 (0.07)	<0.01	1.20
Accuracy [#]	1.38 (0.07)	1.39 (0.16)	0.94	0.04	1.33 (0.12)	1.41 (0.21)	0.17	0.43
Two-Back								
Response Time	2.94 (0.09)	2.94 (0.13)	0.72	0.02	2.92 (0.09)	2.87 (0.07)	0.04	0.61
Accuracy [#]	1.29 (0.17)	1.26 (0.12)	0.81	0.09	1.28 (0.19)	1.38 (0.21)	0.41	0.26

⁺ ES = Effect Size, calculated using Cohen's d for normal distributions and r conversion from z-scores for non-normal distributions, interpreted as small effect = 0.2 – 0.49; moderate = 0.5 – 0.79 or large ≥ 0.8 (Pautz, Olivier, and Steyn 2018).

[#] non-normal distributions - data presented as mean (IQR), p-value calculated from Wilcoxon sign rank test.

4.3.2 CogState Battery

In the Groton Maze Learning Task, the high strike rate innings resulted in a moderate ($r = 0.60$) increase in errors compared to baseline ($w(11) = -2.0$, $p = 0.05$) with no improvement in speed ($t(11) = -0.26$, $p = 0.80$). Following the low strike rate innings there was no difference in number of errors ($w(10) = -0.27$, $p = 0.84$) or speed ($t(10) = -0.67$, $p = 0.52$). Working memory response times following the low strike rate simulation improved moderately ($d = 0.76$) for one-back ($t(10) = 2.1$, $p = 0.03$) but not two-back ($t(10) = 0.4$, $p = 0.72$) responses. Following the high strike rate variant, response times improved ($d = 1.20$) for one-back ($t(11) = -4.5$, $p < 0.01$) and moderately ($d = 0.61$) for two-back ($t(11) = -2.4$, $p = 0.07$) responses.

4.3.3 Psychophysical

Overall, both simulations induced local and central ratings of perceived exertion with an intercept of $\beta = 11.7$ ($SE = 0.7$) with scores increasing until the latter phases. Scores were similar between the 'Close innings' and 'Middle' phases $\beta = -0.6$ ($SE = 0.6$) but, the 'PowerPlay' phase was perceived as less strenuous by $\beta = -4.1$ ($SE = 0.6$) [4.2](#). Local RPE in the high strike rate innings was marginally higher than the low strike rate variant ($\beta = 0.6$ ($SE = 0.3$), $p = 0.049$), while central RPE was similar in both simulations ($\beta = -0.3$ ($SE = 0.3$), $p = 0.432$). Throughout the Low Strike Rate innings, Local and Central RPE were similar ($\beta = 0.04$ ($SE = 0.3$), $p = 0.891$). In contrast, Local RPE was greater than Central $\beta = 0.9$ ($SE = 0.3$), $p < 0.001$) in the High Strike Rate Innings [4.1](#).

4.3.4 Pre-Frontal Cortex Haemodynamics

Change from baseline concentrations of Oxygenated (HBO) and Deoxygenated (HBR) haemoglobin recorded during the CogState battery are presented in Figure [4.2](#). Data processing reduced the useable sample to five athletes in the high strike rate innings and four athletes in the low strike rate innings although only one athlete in represented in both samples. Before the high strike rate simulation, HBO increased by a mean (SD) of $0.55 (0.49) \text{ mmol} \cdot \text{L}^{-1}$, HBR increased by $0.28 (0.32) \text{ mmol} \cdot \text{L}^{-1}$. Similarly, before the low strike rate innings HBO increases by $0.66 (0.31) \text{ mmol} \cdot \text{L}^{-1}$ and HBR by $0.15 (0.19) \text{ mmol} \cdot \text{L}^{-1}$. Following the high strike rate simulation, HBO decreases by $0.56 (0.60) \text{ mmol} \cdot \text{L}^{-1}$ and HBR increases by $0.28 (0.41) \text{ mmol} \cdot \text{L}^{-1}$. Following the low strike rate simulation, HBO decreases by $0.04 (0.40) \text{ mmol} \cdot \text{L}^{-1}$ and HBR decreases by $0.38 (0.30) \text{ mmol} \cdot \text{L}^{-1}$.

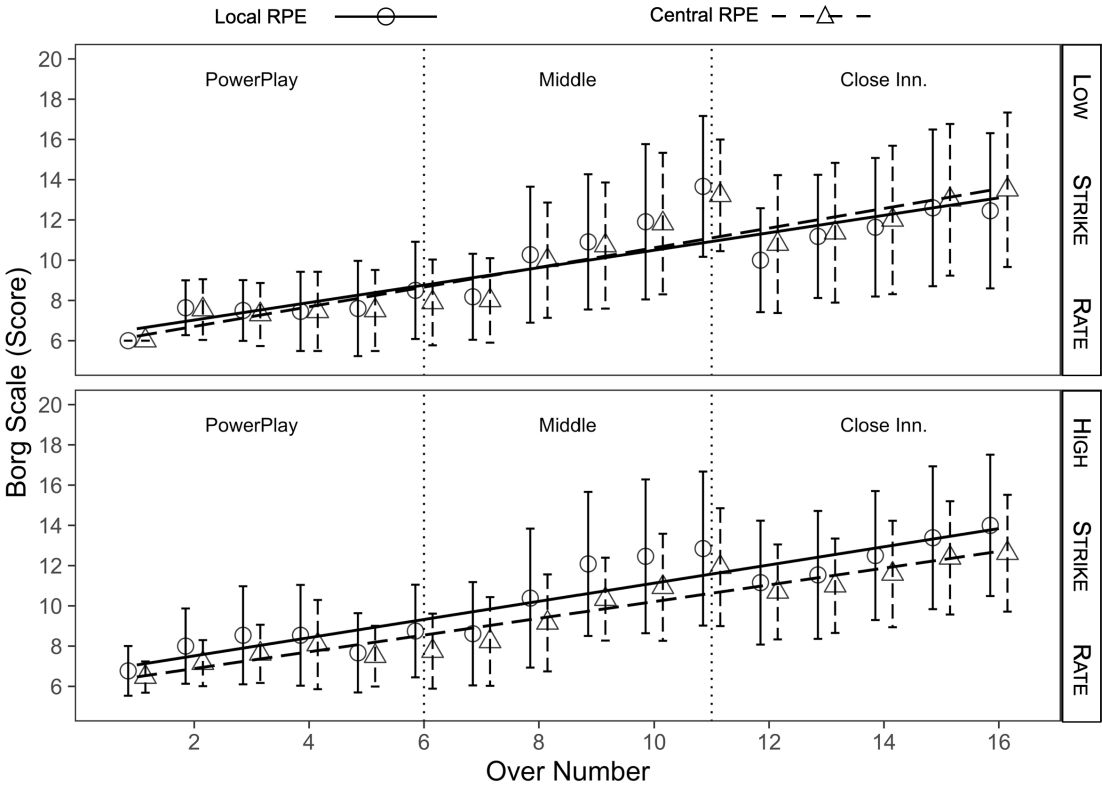


FIGURE 4.1: Ratings of lower-limb musculature (local) and cardiovascular (central) perceived exertion throughout a high and low scoring simulated Twenty20 innings

4.4 Discussion

Few studies have applied cognitive psychological theories to cricket and the present study is the first to investigate batting specific to Twenty20 competition. A batters strike rate appears to be a contributing factor to the cognitive load of an individual, hour-long innings. Following a high strike rate simulation, working memory response times improve but executive functioning appears more error prone. However, in a simulation matched for duration but lower strike rate (120 vs 173) cognitive function is preserved compared to baseline. The haemodynamic response of the prefrontal cortex is altered following both batting simulations when batters performed comparable, cognitively demanding tasks. Trends of oxygenated haemoglobin show blunted concentration increases in response to increasing task difficulty. Finally, central perceived exertion is comparable during both simulations, but the high strike rate innings is perceived as marginally more strenuous to lower-limb musculature.

Batting literature has elucidated that innings duration contributes to observed impairments in cognitive functioning. Evidently, a short batting protocol (30-minutes)

TABLE 4.2: Ratings of central and local (lower-limb) perceived exertion in response to two Twenty20 batting simulations

Phase	‘low’ strike rate			‘high’ strike rate		
	Mean (SE)	LowrCL.	UpprCL.	Mean (SE)	LowrCL.	UpprCL.
Local RPE						
PowerPlay	7.5 (0.8) ^{bc*}	5.2	9.8	8.0 (0.8) ^{bc*}	5.9	10.2
Middle	11.0 (0.8) ^{a†}	8.7	13.3	11.0 (0.8) ^{a†}	8.9	13.2
Close Inn.	11.7 (0.8) ^{a†}	9.4	14.0	12.2 (0.8) ^{a†}	10.1	14.5
Central RPE						
PowerPlay	7.3 (0.7) ^{bc}	5.5	9.3	7.4 (0.6) ^{bc}	5.6	9.2
Middle	10.9 (0.7) ^{a†}	9.0	12.8	9.9 (0.6) ^{a†}	8.1	11.8
Close Inn.	12.2 (0.7) ^{a*†}	10.3	14.0	11.5 (0.6) ^{a†}	9.7	13.3

Phase differences within a simulation $p < 0.01$ - ^aPowerPlay ; ^bMiddle ; ^cClose Inn.

Phase differences between simulations $p < 0.01$ - [†]PowerPlay ; ^{*}Middle ; [#]Close Inn.

elicits no change to cognitive functioning (Neave et al. 2004) while repeated measures throughout a 2-hour protocol concur that functioning is mostly intact in the early stages of an innings, but task performance subsequently deteriorates (Goble and Christie 2017). Our results indicate that when innings duration is constant, striking rates may also contribute to changes in cognitive function. Following the low strike rate innings, delayed-recall working memory response times improve moderately ($d = 0.76$) for recall of one item (one-back) but are unchanged when task difficulty is increased to two items (Table 4.1). Following the high strike rate variant, one-back response times display large ($d = 1.20$) reductions and two-back responses are moderately ($d = 0.61$) reduced.

Numerous studies have reported improvements to response latency during and shortly following physical activity, and theorists often attribute this to exercise-induced arousal (Reviewed by Lambourne and Tomporowski 2010). The adrenal response to physical stress elevates circulating catecholamines and thereafter cerebral concentrations of norepinephrine and dopamine may also increase (Miyashita and Williams 2006; Velasquez-Martinez, Vazquez-Torres, and Jimenez-Rivera 2012). In the PFC, norepinephrine and dopamine work synergistically to control cognitive functioning. Increased cerebral concentrations of norepinephrine increase α_{2A} -receptor firing which increases the strength of neuronal signalling (Roth et al. 1988), while dopamine binds D_1 -receptors to inhibit neuronal signalling to nonpreferred stimuli (Finlay, Zigmond,

and Abercrombie (1995). Resultantly, the batter benefits from the improved ‘signal-noise ratio’ evidenced by the improvement to working memory response times. According to this view, exercise of very high intensity, at or beyond the athlete’s lactate threshold (Borer (2003), causes excessive endocrinological catecholamine release and the oversaturation of norepinephrine in the PFC – impairing the signal-noise ratio by activating low-affinity α_1 -receptors (Arnsten (2011)). Therefore, the batter may find difficulty in executing one decision. In our study, delayed recall working memory improved without detriments to accuracy following both strike rate variants which suggests the cognitive domains assessed by these task sets are not inhibited by the intensity of a Twenty20 innings. Dietrich and Audiffren (2011) propose another theory which attempts to delineate how separate cognitive domains are affected differently by exercise duration and intensity.

The reticular-activating hypofrontality (RAH) model proposes that a significant proportion of neural matter is recruited to sustain and coordinate muscular contractions, especially during whole-body exercise like batting (Dietrich and Audiffren (2011)). Subsequently, structures which are not directly involved in sustaining movement, like the PFC, may forfeit metabolic priority due to the finite limit of neural resources (Audiffren (2016)). Therefore, the authors argue that during exercise, reticular activation (arousal) facilitates cognitive tasks which can be automated through the process of learning/practice, while hypofrontality (reduced PFC blood-flow) at very high intensities will inhibit cognitive tasks which require executive control (Dietrich and Audiffren (2011); Audiffren (2016)). Namely, the RAH model stipulates that the brain has two distinct mechanisms of information processing. An explicit system which requires varying degrees of available working memory capacity and, an implicit system which can function without the input of working memory – subconsciously processed (Evans and Stanovich (2013); Thompson (2013)). The implicit system is favourable when tasks have high temporal constraints as often present in sport (Furley, Schweizer, and Bertrams (2015)). Therefore, in the n-back task which only requires maintenance of a novel stimuli in working memory and a yes/no response to upcoming stimuli, the implicit system is capable of automating task inputs resulting in improved response times in the state of heightened arousal compared to baseline (Dietrich and Audiffren (2011)). However, in the Groton-maze learning task where the explicit system is involved in executive control of working memory to error-monitor and continuously update the visual working memory representation – a moderate ($r = 0.60$) increase in errors emerges following the high strike rate simulation compared to baseline (Table 4.1). Functional-near infrared spectroscopy (fNIRS) of the PFC recorded before the batting simulations show that concentrations of oxygenated haemoglobin increase (a marker of cerebral activation)

when the PFC engages in cognitively demanding tasks. However, following the batting simulations this increase in oxygenated haemoglobin is blunted/diminished [4.2](#). Previous studies implementing fNIRS during an exercise condition have reported that oxygenated and deoxygenated haemoglobin concentrations in the PFC increase during exercise as a function of intensity until intensity exceeds 80% $\text{VO}_{2\text{Max}}$ (Ando et al. [2011](#)). Hence, when the PFC engages in a cognitively demanding task following the batting simulations, PFC oxygenation is still high. But, like Moriarty et al. ([2019](#)), less activation is observed for comparable neural outputs, demonstrating a shift in PFC metabolism potentially related to preceding periods of hypofrontality.

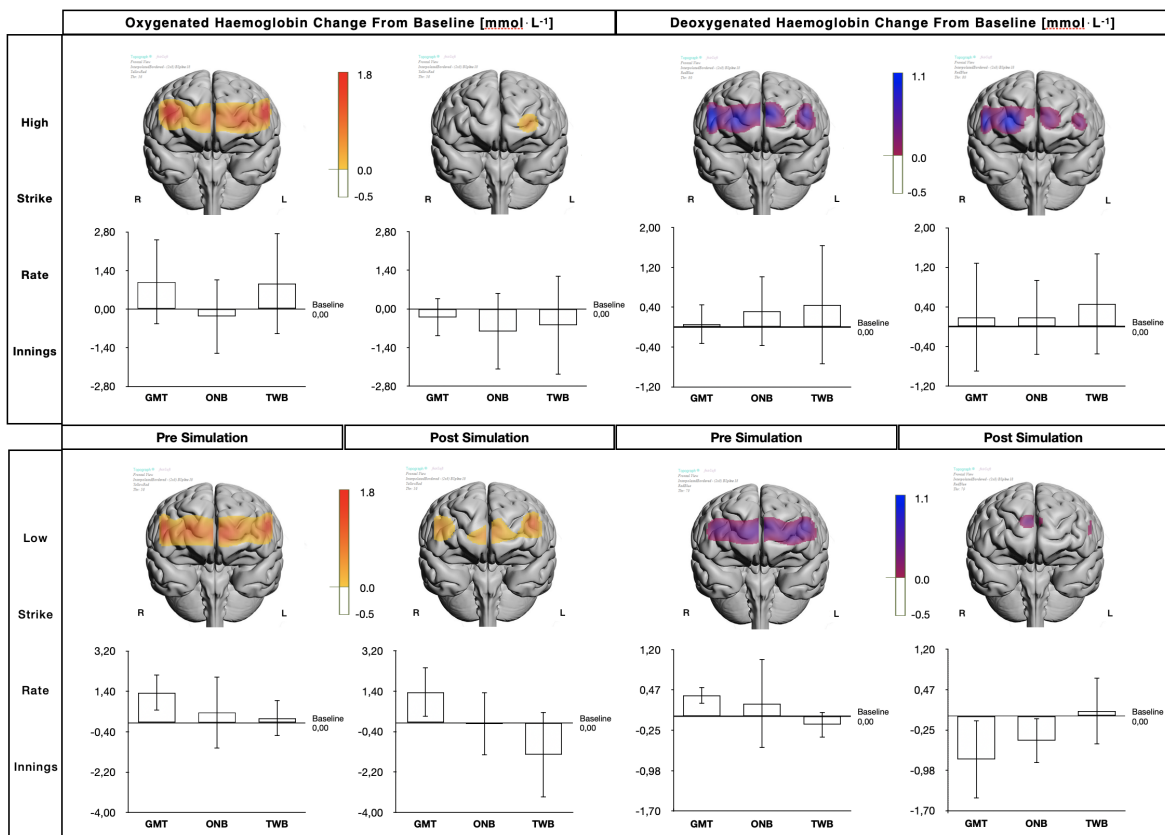


FIGURE 4.2: Concentrations of oxygenated (HBO) and deoxygenated (HBR) haemoglobin overlaid on the PFC and averaged for the duration of three tasks in the cognitive test battery. GMT = Groton Maze Learning Task (executive function), ONB = one-back (working memory), TWB = two-back (working memory).

Run scoring intensity therefore does appear to influence cognitive functioning of the batter in a Twenty20 innings. The high strike rate simulation impaired executive functioning tasks and augmented improvements to visual attention and working memory response times. In the low strike rate innings however, changes in cognitive functioning are less pronounced. According to the RAH model and arousal theories, a

difference in physical intensity/load may explain the discrepancy (Dietrich and Audiffren [2011]; McMorris [2016]). However, perceived exertion was comparable between simulations (Figure 4.1). Batters perceived central fatigue to be identical ($\beta = -0.3$, $p = 0.43$) and local fatigue was marginally higher in the high strike rate variant by $\beta = 0.6$ points, $p < 0.01$. Further, perceived exertion increased linearly with innings duration [4.1], indicating that a Twenty20 innings may not provide undulations in intensity present in longer match formats (Goble and Christie [2017]). Perceived exertion is understood to compete for attentional resources therefore acting as a psychological deterrent to accurate cognitive functioning (Tucker and Noakes [2009a]; McMorris [2021]). In both simulations perceived exertion peaked in the final phase (Figure 4.1) which coincides with the period of peaking run scoring intensities. In this period, high-risk, aerial, strokes are urged to achieve boundaries as the risk of being dismissed is less emphasized. It is conceivable that the switch in tactic further restricts the temporal constraints placed on the batter. To increase the likelihood of scoring boundaries, the batter must impart greater velocity to the ball which is achieved by increasing bat velocity and therefore the kinematic forces at ball-impact (Peploe et al. [2019]). The increased bat velocity and accompanying inertia provides little leeway for the stroke to be corrected once initiated (Sarpeshkar and Mann [2011]). Therefore, the batting task may shift from being reactive/opportunistic to oncoming stimuli, towards a more pre-emptive task demanding forceful stroke production regardless of upcoming stimuli. Resultantly, the batter is more reliant on implicit processing, quickly deriving and executing a response from the earliest availing stimuli. Thus, in the simulation which enforces more boundary requirements, particularly at the end of the innings, and close to the second cognitive assessment, functioning is consistent with predictions from the RAH model. We speculate that in skilled batters who are acclimatised to performing under heavy exercise, the desired run scoring intensity of an innings may modulate cognitive functioning to further favour implicit processing, at the expense of executive control.

The practical implications are as follows. During an innings, it is likely that a batter's cognitive efficiency will change to compensate for the physiological stress of whole-body exercise (Dietrich and Audiffren [2011]; McMorris [2016]). Implicit processing streams, like the batter's ability to perceive a kinematic signature in the bowler's action which correspond to a learned instance – are likely facilitated (Dietrich and Audiffren [2011]; McMorris [2016]). In other words, exercise-induced arousal accelerates the batter's ability to initiate and execute strokes. However, it is plausible that deficits to explicit processing streams are present, especially at increasing/very high striking rates. It may therefore be advisable to ensure that batters have pre-determined solutions to

strategies opposing bowlers may employ, rather than assessing fielding positions and risk-reward ratios of different strokes live.

Limitations and Future Research Direction

Although this study attempted to provide novel data specific to Twenty20 cricket, a number of considerations could be made for future studies. Variables of PFC haemodynamics could not be subjected to desired statistical scrutiny due to data integrity not withstanding recommended post-processing. Thus, smooth-motion artefacts account for the majority of lost data. A cognitive component of batting is absent due to the use of a bowling machine. Therefore, future studies should investigate how live bowlers affect information processing streams, particularly the batter's ability to switch between implicit and explicit processing. Further, the timing of cognitive assessments and their applicability to cricket should be considered. Although validated methods of assessing acute changes to cognitive function, like CogState, are readily available, these assessments remove batters from the cognitive context of batting to perform computer-based tasks. Naturally this raises uncertainty on the relevance of obtained data and whether it is directly applicable to cricket. In other sports, assessments which attempt to quantify the speed and accuracy of cognition which use task designs that mimic the decisions present in competition have been implemented (Furley, Memmert, and Heller 2010; Furley and Memmert 2013). These tasks also allow cognitive assessments to be conducted concurrently while the athlete is performing which is advantageous when studying the combined effects of physical and cognitive stress. Finally, these assessments may be beneficial to athlete performance enhancement in coaching programs or as a cognitive warm-up pre-innings.

Conclusion The run scoring rate of an individual Twenty20 innings moderates the cognitive strain experienced by the batter. A high strike rate innings decreases working memory response times of batters, but results in increased executive functioning errors. An innings with equal overall duration, off-strike runs scored and on-strike deliveries faced, but runs scored at a lower strike rate (120 vs 173), results in less pronounced cognitive fatigue. It is conceivable that the distribution of cognitive and physical efforts when batting at high strike rates, results in compromise of high-order cognitive performance. The exact detriment of suppressed executive functioning to batting performance is yet to be fully studied, however, it can be theorized that batters will be error-prone when strategising or planning during an innings. Therefore, the bulk analysis of tactics and strategy should be practised prior to an innings. Allowing batters

to apply solutions reactively to availing match stimuli, rather than generating these solutions live.

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Disclosure statement

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Chapter 5

Measuring Sport Specific Psychomotor Function - Phase 3

The results presented in Chapter IV highlight current limitations of cognitive research in sport. Validated methods available for quantifying acute changes in cognitive efficiencies are not designed to measure task-specific or ecological cognition. Therefore, it is difficult to interpret consequences to batting performance from tasks which are discrepant from the task of batting. In other words, cognitive efficiencies of batter's should be interpreted from parameters of batting performance or, tasks which consider the performer-environment interaction of batting.

The following chapter attempts to provide a rationale and methodology to quantify psychomotor performance which is more ecological to the task of batting.

Contribution of Authors;

T Lopes - conceptual design, data collection and analysis, data visualisations and writing

S Kerr - supervision, proof-reading and editing

B Olivier - supervision, proof-reading and editing

Pitch Reaction Test – Stepping towards a novel measurement of batting cognition

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Abstract

Little is known about the cognitive acuity of batters in cricket. Potentially this data is limited due to the lack of practical methods of assessing cognitive function congruently while batting. In this study we describe the development of a choice reaction task paradigm which is deployed on a cricket pitch. The Pitch Reaction Test (PRT) analogues the initial central processing and motor response of stroke selection to quantify psychomotor performance. A prototype PRT was assessed in a laboratory to model its measurement accuracy against reviewed slow-motion footage of motor responses from 15 trials of 23 participants. Linear models compared PRT performance vs an established computer-based task and user anthropometry. Measurements obtained from the PRT were strongly correlated with review of video footage ($r = 0.97 - 0.99$), although Bland-Altman analysis reveals a linear trend of differences increasing with increases in mean response times. Neither participant height ($\beta = -0.01$, $p = 0.54$) or leg-length ($\beta = 0.0$, $p = 0.58$) were predictors of PRT performance. Choice response performance on an equivalent computer assessment has a weak ($R^2 = 0.16$) negative relationship ($\beta = -0.21$, $p = 0.04$). Overall, the PRT demonstrates a novel solution to measuring sport specific psychomotor function in cricket enabling multiple avenues of future research.

Keywords: batting, psychomotor, response time

5.1 Introduction

The cognition of cricket batters has not been extensively studied and authors have questioned if data from standardised, cognitive component ‘pen and paper’ assessments can be generalised to describe sport-specific performance (Goble and Christie 2017). Another approach attempts to quantify a sport-specific cognitive parameter by mimicking the stimuli, temporal constraints, and information processing stream of match-play. For example, Furley, Memmert, and Heller (2010) assessed visual awareness by presenting game scenarios depicting whether players are available or unavailable to receive a pass. The task paradigm enabled the authors to manipulate and discuss how the contents of the athletes working memory may bias the athletes’ attentional mechanisms to seek similar contents in the current visual field. Importantly, such data provides objective, practical implications for performance enhancement and the coaching environment.

In cricket, a parameter of cognition critical to batting performance is psychomotor function (Portus and Farrow 2011; Sarpeshkar and Mann 2011). That is, the cognitive processing of visual and perceptual stimuli coupled with a complex movement behaviour (Miller and Low 2001). The extreme temporal constraints of intercepting a high-velocity cricket ball requires substantial processing speed of specific contextual stimuli (bowling action, ball flight). Coupled with precise, rushed movement responses – Sport Specific Psychomotor Function (SSPF) (Habay et al. 2021). Therefore, a method of quantifying SSPF, mimicking sensory-motor characteristics of batting, may provide much needed data for research with practical insights for the game.

The aim of the current study is to propose a task paradigm and design to quantify SSPF in cricket. The chosen task paradigm is analogous to established assessments of psychomotor function – response time (milliseconds) to distinguishable stimuli with corresponding distinct inputs/responses (Miller and Low 2001). The design provides a means of conducting assessments on a cricket pitch, concurrently with batting. The distinguishable stimuli, in the form of coloured lights, mimic the potential locations that deliveries will impact and bounce. The corresponding movement response is to initiate a ‘front foot’ or ‘back foot’ stroke by completing either a forward or backward lunge. A prototype device is developed and tested for recording accuracy against a high-speed camera.

5.2 Methods and Materials

5.2.1 Pitch Reaction Test - Background

In one trial of the PRT, the subject assumes the posture of a batter – knees slightly bent and shoulders parallel to the light stimuli placed lengthwise down the artificial pitch. In this starting position, the subject places both feet in a defined position demarcated on the turf. The ‘front foot’ is placed closest and perpendicular to the light stimuli and the ‘back foot’ placed similar but distal from the light stimuli by approximately shoulder width. The light stimuli mimic the incoming direction of deliveries from the bowler and two distinct categories or locations where the delivery will bounce. In cricket, a delivery can be coarsely categorised based on the distance a delivery impacts the pitch causing it to bounce in front of the batter. The height of a given delivery when it reaches the batter is therefore determined by the location of bounce. Deliveries which bounce further from the batter (called ‘short’ deliveries) have more length of the pitch to travel and gain incline compared to deliveries which bounce close to the batter (‘full’) and are therefore intercepted before regaining much height. Importantly, the category of delivery, either short or full, determines the primary movement the batter must complete to successfully intercept the delivery. Short deliveries tend to reach the batter at above chest height and ideally should be redirected back towards the ground requiring the batter to remain fully upright at interception. In contrast, for a full delivery, the batter will move towards the location of bounce, ideally intercepting the delivery low to the ground, smothering the potentially unpredictable bounce.

Using this concept, the PRT displays a stimulus at either a full length or short length, then assesses the latency of the batter/subject’s decision and movement response to the stimuli. A simple, dependable circuit was designed to 1) display a light stimulus (green light) at one of two locations along the length of a cricket pitch and 2) measure the latency in milliseconds between stimulus presentation and user-input/response at the users’ feet. Software on and delivered to a microprocessor (Arduino, Ivrea, Italy) oversees the randomisation of circuit behaviour i.e., which location displays a green light and the delay between successive trials/stimuli. An outline schematic of the device and circuitry is drawn in Figure [5.1](#)

5.2.2 User Input or Instructions

For short deliveries, the light stimuli most distal from the subject is activated – to respond the subject’s back foot must move from its starting position further backward to a defined location demarcated on the turf, keeping the front foot in contact with

the ground at its starting position. For full deliveries, the light stimulus closest to the batter is activated, to respond the front foot moves forward to a defined location, back foot remaining in contact with the ground.

5.2.3 Hardware

The PRT can be sub-divided into three functional units. The first unit being an array of four 650nm 5mw red dot lasers (Electronics International Enterprise, distributed by ManTech Electronics, South Africa) connected in series to an independent source of 5V direct current. The lasers are mounted onto circuit boards and fixed to a wooden rail at predefined distances corresponding to the starting and response-ending positions of the front/backfoot [5.1](#). The second unit is a complementary sensory array of four, 20mm diameter, photosensitive variable resistors (Senba Optoelectronic, Shenzhen, China). Mounted to circuit boards and fixed to a second wooden rail, the sensor height from the ground is 0.5cm. The variable resistors are semiconductive materials with a peak response sensitivity to 500-700nm light. The sensory and laser array are placed parallel 2m apart and each laser points perpendicularly to the opposite wooden rail towards its paired variable resistor on the sensory array. The third functional unit is connected to the sensory array via Network LAN cat6 cable. One LAN cable from each photosensitive resistor connects to four analogue pins of the Arduino Nano (Arduino, Ivrea, Italy) mounted on a circuit board. The output of the Arduino Nano is also delivered via LAN cat6 cable, instead using three digital pins to control one LED. Two LEDs were controlled by the Arduino Nano, one placed 2.5m from the starting “front foot” position and the second 6m from this position. Therefore, the third functional unit can be conceptualized as the processing and control unit – processing signal from the complimentary laser-sensory arrays and controlling the behaviour/activity of the two LEDs.

The PRT analyses movement of the users’ feet by measuring total resistance ($m\Omega$) at the four circuits of the sensory array. When exposed to direct, bright light the total resistance applied by the photosensitive resistor to its circuit is reduced by 600-700 $m\Omega$. When a user stands at the front and backfoot starting positions, the corresponding photosensitive resistors are occluded from their paired lasers by the users’ feet/lower limbs. The remaining two sensory circuits receive unimpaired light from their corresponding lasers and therefore total resistance measured at these circuits is 600-700 $m\Omega$ less than at the occluded circuits of the starting position. The photosensitive resistors are validated to respond to changes in lux (light brightness) in 30ms. When responding to a stimulus, the user’s foot will move from the starting position, providing

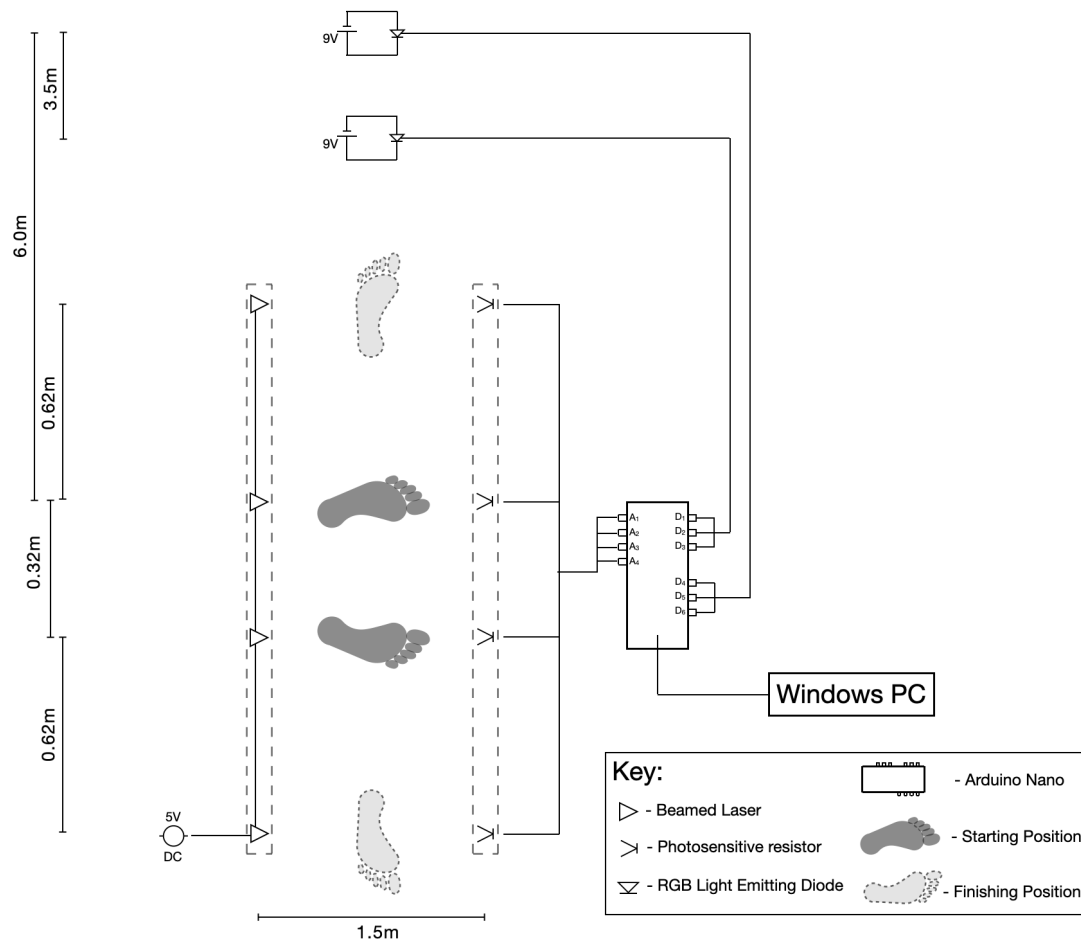


FIGURE 5.1: Schematic of Pitch Reaction Test componentry and layout
- not drawn to scale

the corresponding sensory circuit with unimpaired light, and finish at the demarcated end position on the turf – occluding its corresponding sensory circuit, increasing total resistance by 600-700 mΩ.

5.2.4 Software

The functioning of the PRT is enabled by two scripts written in Arduino Programming Software (Arduino, Ivrea, Italy) and Python programming language v3.1 (Van Rossum and Drake [2009](#)). To summarize, the Python script entails the following instructions/functions; i) generate a random integer between 0 and 1 from a binomial distribution, ii) convert the integer to a character string of “front” ($> 0 \times \leq 0.5$) or “back” ($> 0.5 \times \leq 1.0$), iii) return one random letter between A-G from a polynomial distribution, iv) send combination of generated character string and letter (e.g. frontA) to Arduino, v) compile signal returned from the Arduino into a .txt file.

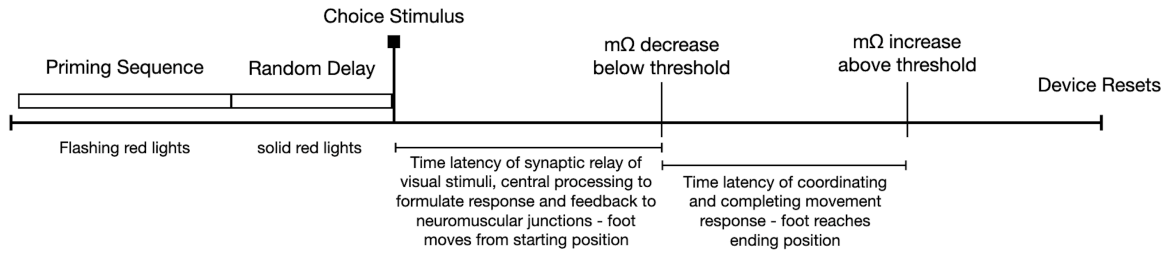


FIGURE 5.2: Sequence of events and measurement cut-offs at starting and ending sensory arrays

The output from the Python code is delivered to the Arduino Nano and the micro-processor is initialized with a script containing the following instructions/functions; i) intermittently power both LEDs to display red light in a sequence of 100ms powered and 1500ms rest – the rest interval is then halved every cycle providing the impression of increasing speed/frequency, this is the priming sequence, ii) power both LEDs to display red light for a defined period by interpreting the received signal where $A = 400\text{ms}$, increasing in 200ms increments till $G = 1600\text{ms}$, iii) interpret character string from received signal to power corresponding LED circuit with green light and rest the alternate LED circuit iv) calculate the interval between powering the LED circuit and total resistance reaching threshold at the corresponding sensory circuit (front or backfoot starting position), v) calculate the interval of reaching resistance threshold between the starting and finishing position. vi) send both calculated intervals to the connected windows PC.

Thresholds of total resistance were defined to consistently label events occurring at the sensory circuits where photosensitive resistors have a response time of 30ms and total resistance is continuously measured at 1000Hz . Therefore, at sensory circuits of the starting positions where sensors are occluded the threshold was labelled as $< 200\text{m}\Omega$ and $> 600\text{m}\Omega$ for the sensory circuits at ending positions. Hence, two variables are obtained from one trial of the PRT. One measurement of the interval between stimulus presentation and primary responsive movements – this can be regarded as pre-motor time i.e., time to register, process and respond to stimuli. And a second measurement of the interval between first movement and completion of movement/response. The summation of both measures can be regarded as choice-response motor time.

A calibration function in the Arduino code provides a live trace of output from the sensory circuits. The live trace (Arduino IDE serial plotter) was used to verify that each sensory circuit reached threshold in obscured and unobscured conditions ensuring

no interference is caused by ambient light. The calibration script was run before every subject was assessed.

5.2.5 Procedural Overview

The measuring accuracy of the developed device was assessed in a single-assessment laboratory study. The study was conducted in The Movement Physiology Research Laboratory at the University of the Witwatersrand, South Africa. The Pitch Reaction Test (PRT) was set-up on an artificial turf with length = 12 meters and width = 3m under artificial lighting. In the quiet laboratory, a PC was set-up for participants to perform a seated cognitive assessment of response times with a task domain akin to the PRT. Healthy males ($n = 10$) and females (13) were recruited within an age range of 18-30 years. In approximately 1 hour, participants were habituated to the PRT, performed the computer-based cognitive assessment, and thereafter the final assessment using the PRT. Anthropometry was also collected prior to these assessments.

Ethics Statement

The aims and procedures of the study were carefully explained to participants who thereafter signed voluntary informed consent. All procedures were reviewed by the Human Research Ethics Committee (clearance no: M171165)

To habituate participants to the PRT, the device was initiated to run continuously during the demonstration. Participants performed an undefined number of trials until satisfactory task proficiency, judged as 15 consecutive correct responses, was demonstrated. Assessing the learning response to the PRT was beyond the scope of this experiment, therefore satisfactory task proficiency was deemed on ability to provide data to validate the recording accuracy of the PRT and not a required threshold of performance. For the final PRT assessment, a camera (GoPro Hero8, San Mateo, USA) was set-up 8cm above the artificial turf capturing view of both light stimuli and lower limbs of the participant. Before starting the final PRT assessment, the camera was initiated to record at 240 frames per second for the entirety of the assessment.

5.2.6 Anthropometry

Stature was recorded to the nearest 0.5cm using a stadiometer. True leg length (Gogia and Braatz [1986](#)) was recorded to the nearest 0.5cm using a tape measure placed at the bony prominence of the iliac crest and medial malleolus. Both legs were measured to obtain an average.

5.2.7 Established computer-based cognitive assessment

A brief test battery in Psytoolkit (Stoet 2017) was saved for all participants to perform. The test battery included two tasks, simple response time and choice response time respectively for all participants. In the simple response time task, participants react to a single stimulus by pressing one possible input on the keyboard. The stimulus is a black 'x' which appears in a white checkbox. Participants are instructed to respond by pressing the space bar as soon as the 'x' appears. Upon providing the correct keyboard input the task resets, displaying an empty white checkbox and the cycle repeats with unpredictable delays to stimulus presentation. The choice response task operates similarly but, requires input to one of four possible stimuli by pressing one of four corresponding keyboard inputs. Four white checkboxes are displayed at the centre of the display and the two leftmost boxes correspond to input from adjacent keys 'z' and 'x' while the two rightmost boxes use adjacent keys of the comma and full stop. Before starting either task, the user is given written instructions and several practice trials with feedback.

5.2.8 Analysis of high-speed video footage

Data was reduced from slow-motion video footage of participants performing trials of the PRT. Elapsed time in video can be calculated if the number of frames present/captured between two events and the frequency of still frame capture (frame rate) set by the camera is known. In our experiment, footage was recorded at a rate of 240 frames per second, therefore, a still frame is captured every 4.1667 milliseconds. The footage provides visible confirmation of both LEDs displaying red light (randomised delay) and the transition to providing choice stimulus (green light at one LED) to the user. The first frame where the choice stimulus becomes apparent is therefore the reference frame and the number of frames following describe the elapsed time from stimulus presentation. A criterion for defining and marking events of movement in the video footage which can be compared to measurements of the PRT was required. Examples of still frames and their movement criterion are shown in Figure 5.3. Four key events of movement response were chosen – two events at the location of the starting foot position (first measurement obtained by the PRT) and two events at the finishing foot position (second PRT measurement). The rationale of how key events were defined was to critically assess the recording accuracy of the PRT for use in research and practice settings. For example, the criterion of key event labelled A - Initiation Figure 5.3 is the first frame which displays any sign of movement – a visible deflection in the position/shape of the laser on the user's foot. The next event, labelled B – Lift-off, has

criterion of the first frame displaying complete clearance between the user's foot and artificial turf. Considering how measurements are obtained at the sensory circuits of the PRT, the key event A – Initiation identifies the first signs of responsive movement at the user's feet but, not enough movement to have the sensory circuit unobscured. Conversely, the event B – Lift-off describes an event where the movement response has advanced and the sensory circuit, $\pm 0.5\text{cm}$ above the turf, could be partially exposed to light or unobscured light existed while a part of the foot continues to break contact with the turf. It was therefore hypothesized that measurements obtained by the PRT would lie within the window of key event A and B indicating strong agreement between elapsed time calculated from video footage and measured by the PRT. Thereafter, the application and clinical accuracy of the PRT can be assessed by judging the magnitude of the time frame between event A and B.

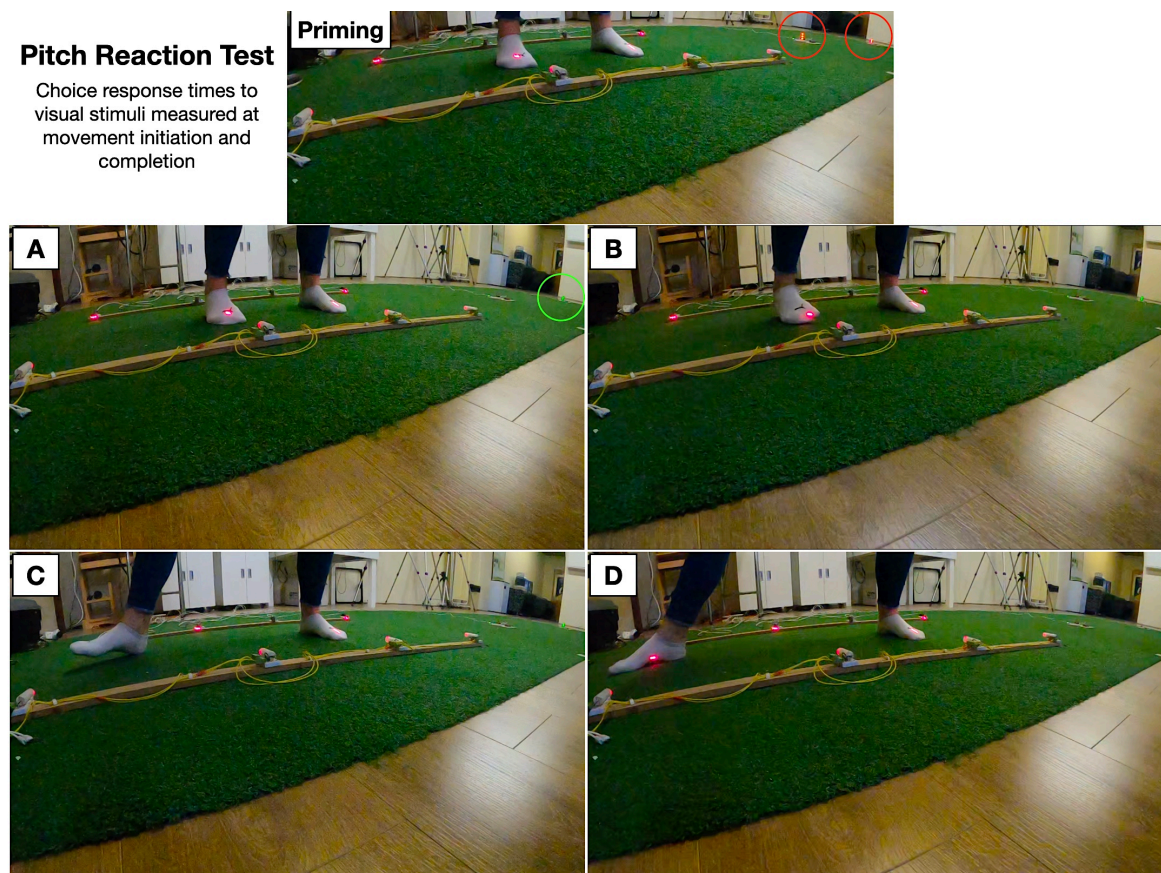


FIGURE 5.3: Outline of key events during one trial of the Pitch Reaction Test. Top image depicts the sensory priming phase where both choices pulsate for a randomized time delay before randomly presenting a ‘go’ signal (green light) at one of the available choices – front foot or back foot. Image labelled A depicts *Initiation* of movement, the first frame with a visible deflection of the laser on the athlete’s foot after being presented the go signal. Image B depicts movement *Lift-off*, the first frame with visible clearance between the athlete’s foot and artificial turf. Image C depicts *Point of Contact*, the first frame with visible contact of the athlete’s foot with the artificial turf at the position of correct choice to the stimuli presented – in this case stimuli presented at back light requires back-foot movement. Image D depicts end of movement or *Finish*, the first frame where the athlete’s foot makes complete contact with the turf. The go signal is deactivated once the PRT detects a correct response and the cycle repeats for subsequent trials.

5.2.9 Data Analysis

Each participants performed a total of 15 trials in the assessment. All data were tested for homoscedascity from Q-Qnormal plots and passed Shapiro-wilk test for normality. Multiple linear models assessed the strength of relationship between measures obtained from the PRT and calculated at each key event from video footage. Pearson correlation

TABLE 5.1: Height and true leg length of male and female participants

	Male (n = 10)		Female (n = 13)	
Height (cm)	171.5	(7.3)	165.7	(5.5)
True Leg Length (cm)*	89.3	(6.4)	86.5	(4.5)

Data presented as mean (SD)

* True leg length measured from iliac crest to medial malleolus according to method of (Gogia and Braatz 1986)

coefficients (r) were also calculated for each key event. Bland-Altman analysis is also performed to determine the mean difference and limit of agreement between the two methods at each key event. From mean values, linear models assessed the relationship between the mean response time achieved on the PRT by each participant against the mean response time achieved on the simple and choice reaction tasks of PsyToolkit. Finally, linear models of the relationship between participant height and true leg length with mean PRT response times are performed.

5.3 Results

Anthropometric variables of 23 recruited participants, mean age 24 years ($SD = 2$), are summarised in Table 5.1.

5.3.1 PRT comparison to high-speed camera

Across all trials, response times measured at the sensory arrays of the PRT recorded a mean(SD) of 765.7 (256.4)ms at the starting position and 1023.6 (322.9)ms at the finishing position. Whereas, measures from slow-motion video footage reveal a mean(SD) of 782.7 (295.3)ms at event A - Initiation, 855.2 (295.2)ms at B - Lift-off, 1186.4 (367.3)ms at C - Point of Contact and 1259.8 (377.2)ms at D - Finish.

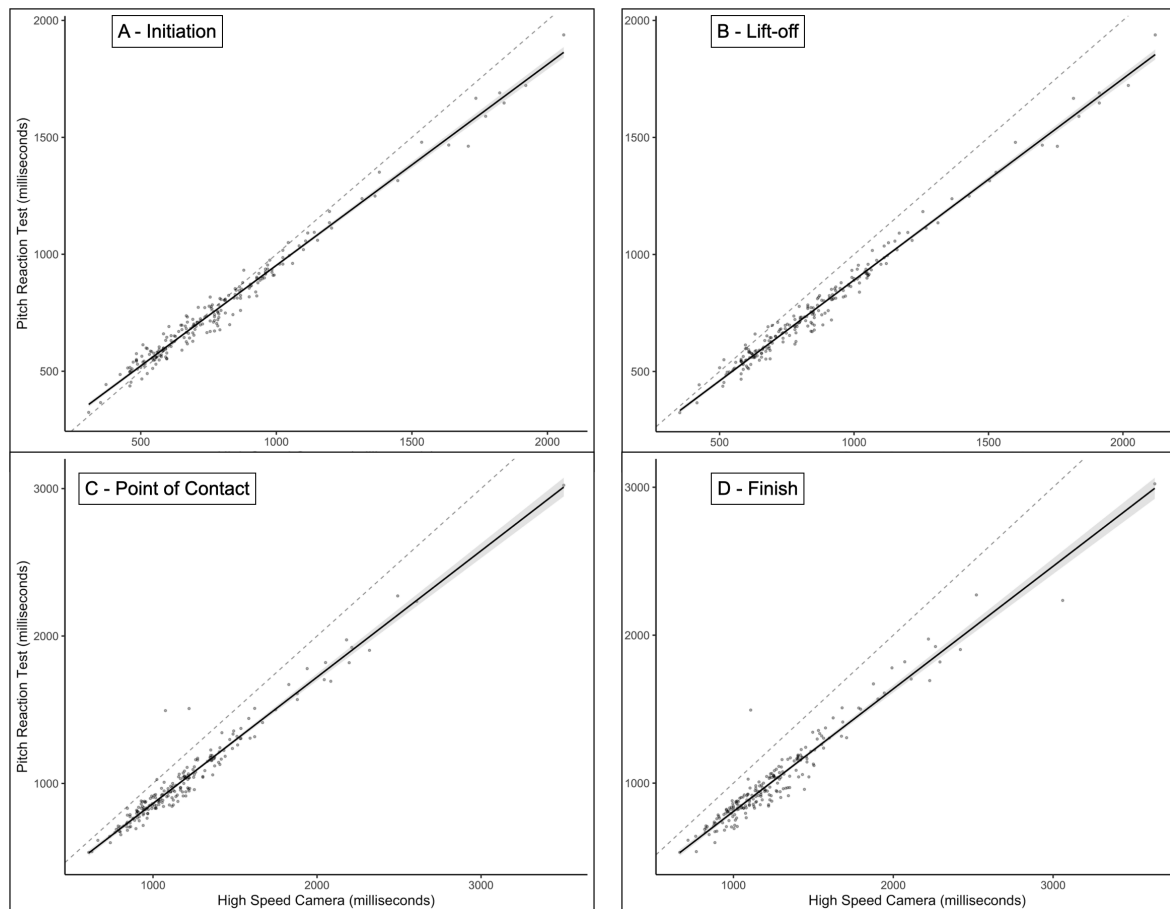


FIGURE 5.4: Linear models comparing measurements calculated at each key event of video footage with measures obtained from the PRT. Solid line indicates applied model and grey shaded area represents the 95% CI. Dotted line represents a line of best fit with intercept = 0 and slope = 1

Elapsed time between presentation of stimulus and primary movement response measured by the PRT and high-speed camera were correlated at A - Initiation ($r = 0.990$) and B - Lift-off ($r = 0.991$). Similar, measures between stimulus presentation and final movement were also correlated at C - Point of Contact ($r = 0.975$) and D - Finish ($r = 0.970$). Figure 5.4 compares elapsed milliseconds recorded by both devices at each interval, with a line of perfect agreement (slope = 1, intercept = 0) and calculated linear models presented in Table 5.2.

In the Bland-Altman analysis, the mean difference between measures increased from 17.0ms measured at movement A - Initiation, to 89.4ms at B - Lift-off, 162.8ms at C - Point of Contact and 236.2ms at movement D - Finish (Figure 5.5).

TABLE 5.2: Co-efficients of agreement and correlation between the PRT and high-speed camera at each key event of movement

Event	β	tstat	$\Pr(> t)$	R^2	pvalu
Initiation	1.14	99.95	<0.001	0.98	<0.001
Lift-off	1.14	104.86	<0.001	0.98	<0.001
Point of contact	1.11	63.03	<0.001	0.95	<0.001
Finish	1.13	55.61	<0.001	0.94	<0.001

R^2 : coefficient of determination

5.3.2 Correlation with subject anthropometry and equivalent seated task performance

Choice response times at the computer-based task showed a weak ($R^2 = 0.16$, $F = 4.61$, $p = 0.04$) negative relationship to PRT performance ($\beta = -0.21$, $t = -2.15$, $p = 0.04$). One item response times were not predictive of PRT performance ($\beta = -0.07$, $t = -1.44$, $p = 0.17$) – Figure 5.6. Neither subject Height ($\beta = -0.01$, $t = -0.63$, $p = 0.54$) or Leg Length ($\beta = 0.00$, $t = -0.56$, $p = 0.58$) were significant predictors of PRT performance (Figure 5.7).

5.4 Discussion

The developed PRT demonstrates a practical solution to measuring the speed of cognitive, psychomotor function in cricket players in the playing environment. Measurements calculated from video footage and the PRT are strongly correlated, although a deviating trend is visible. Height and leg length do not appear to be strong predictors of PRT performance. There's a weak negative relationship between choice response times on the computer-based assessment and the PRT.

The measurements obtained by the PRT show a strong relation to those calculated from video footage. At all four key events, the PRT is correlated to within $r = 0.98 - 0.99$ of the high-speed camera (Figure 5.4). Linear models, however, do not show a perfect relationship of gradient and intercept or line of best fit (gradient = 1, intercept = 0). Instead, coefficients range from $\beta = 1.11 - 1.14$ indicating that the PRT records measurements which are smaller in magnitude i.e., faster response times by 2-19%. The trend is further clarified by Bland-Altman analysis at each key event. The mean difference between measures obtained by the PRT and high-speed camera is smallest at event A – Initiation (17ms) and thereafter increases at each subsequent event till a difference of 236ms is observed at event D – Finish (Figure 3). Further, differences between the PRT and high-speed camera increase linearly within each key event (Figure

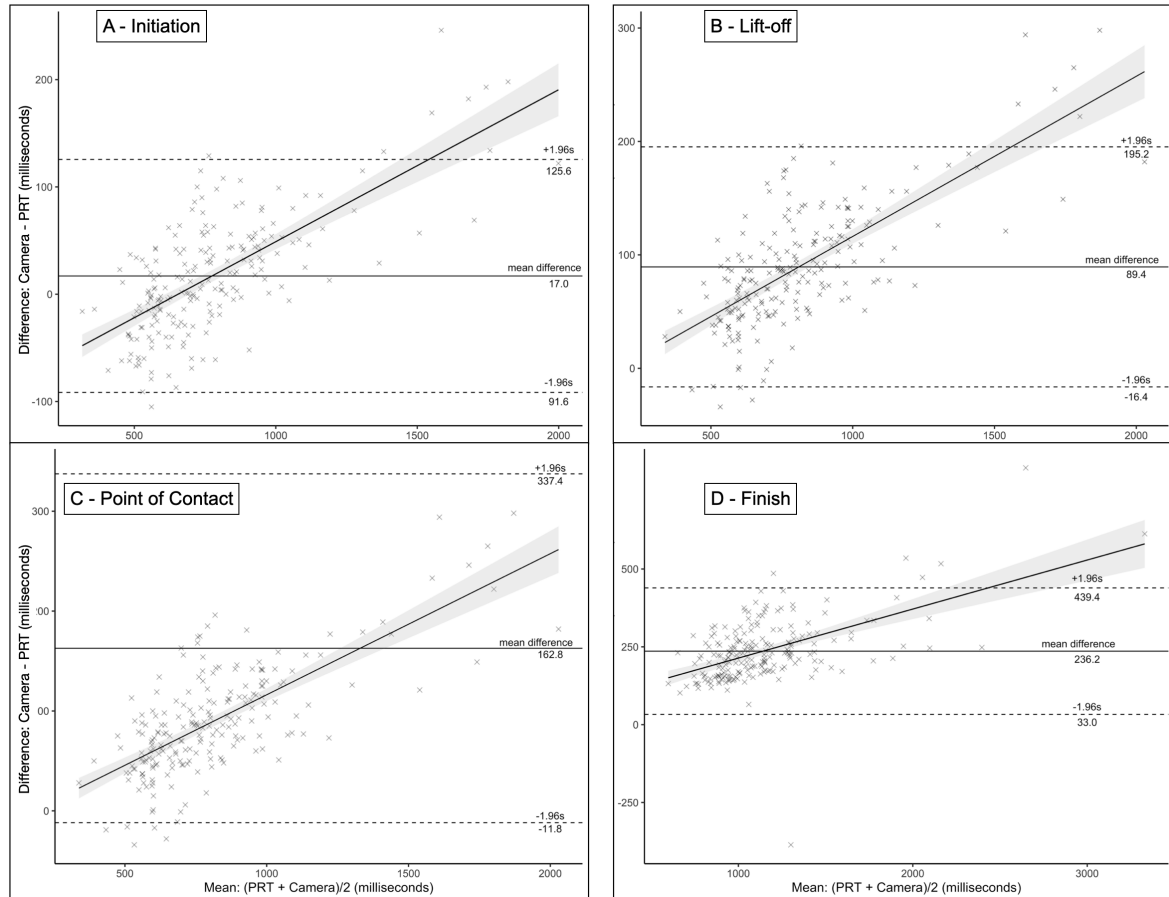


FIGURE 5.5: Bland-Altman analysis comparing mean difference and limits of agreement at each key event. Dotted lines represent upper and lower limits of agreement and solid horizontal line represents mean difference. Overlaid linear models with 95% CI shaded in grey are also applied showing linear relationship between mean response times and differences between methods

5.5) as the mean response time increases. In other words, slower responses produce less agreement and greater difference between methods.

The progressive increase in disparity therefore shows that methods initially diverged, and accuracy is steadily lost, although precision/consistency in measurement is present (Figure 5.4). Considering the strong linear relationship between methods, if it is assumed that the high-speed camera method obtains more accurate measurements, PRT measures can be recalculated to increase by $\beta = 1.1 - 1.14$ times to reflect the camera. We postulate that the high-speed video method steadily loses accuracy due to variability in still frame capture leading to accumulation of error. That is, at 240fps in 1000ms a still frame is captured on average every $1000/240ms$. Therefore, the first still frame to capture the green light stimuli displayed by the PRT is $\pm 4.166ms$ imprecise to the true moment of appearance. Subsequent still frames continue to approximate by

$\pm 4.166\text{ms}$ and resultant error accumulates as a function of multiplying over several still frames. Introducing more still frames then, as expected at the latter events of movement (C, D) or slower responses, will result in more accumulation of error and less agreement between methods.

A device like the PRT is undoubtedly more practical than measuring response times to visual stimuli from high-speed video footage. Although the true accuracy to reality cannot be fully concluded with the data and method presented in this study. The components of the PRT have a theoretical sensitivity of $\pm 30\text{ms}$ which should supply sufficient resolution to defer clinical significance changes in response time performance (Brown and Heathcote 2008). The PRT shows potential for use in research and practice where measuring acute and longitudinal changes to response time performance within an individual are valuable. To further explore the utility the PRT, test-retest reliability should be assessed.

Given the sparsity of data surrounding the cognitive faculties of batters, a quantitative assessment of cognitive performance which is deployed on the field can aid in answering several hypotheses. Studies have shown that the effects of physical exertion on cognition quickly fade when activity is stopped (Jung et al. 2022; Sudo et al. 2022). A device like the PRT allows parameters of cognition to be assessed concurrently with a prolonged, fatiguing batting innings. More parameters of cognition could also be considered in the test battery of the PRT. For example, although not fitting within the scope of this study, the developed python and Arduino scripts also provide a means to assess response inhibition (Congdon et al. 2012). In the task paradigm of Go/No Go tasks, stimuli can be classed into responding stimuli (single green light in this scenario) and non-responding stimuli. Non-responding stimuli somewhat mimic the appearance of responding stimuli but require executive control to inhibit the accustomed response to prepotent stimuli (Congdon et al. 2012). In our scenario, the combination of Python and Arduino code provide function for a non-responding stimulus to be delivered randomly in 20% of trials. Following the normal priming sequence and randomised delay, a mimicking stimulus (non-green light at one LED location) is delivered, and no movement response must be seen. The minimal addition to code enables two categories of tallying errors (accuracy) to be complimentary measured with response time (speed). A movement response to a green light, but to the incorrect direction is classified as a 'legal error' error and any movement response to the mimicking stimuli 'inhibition/commission' error (Pietrzak et al. 2008). These error classifications may supply additional insight to higher-order, executive processing performance (Pietrzak et al. 2008; Chambers, Garavan, and Bellgrove 2009).

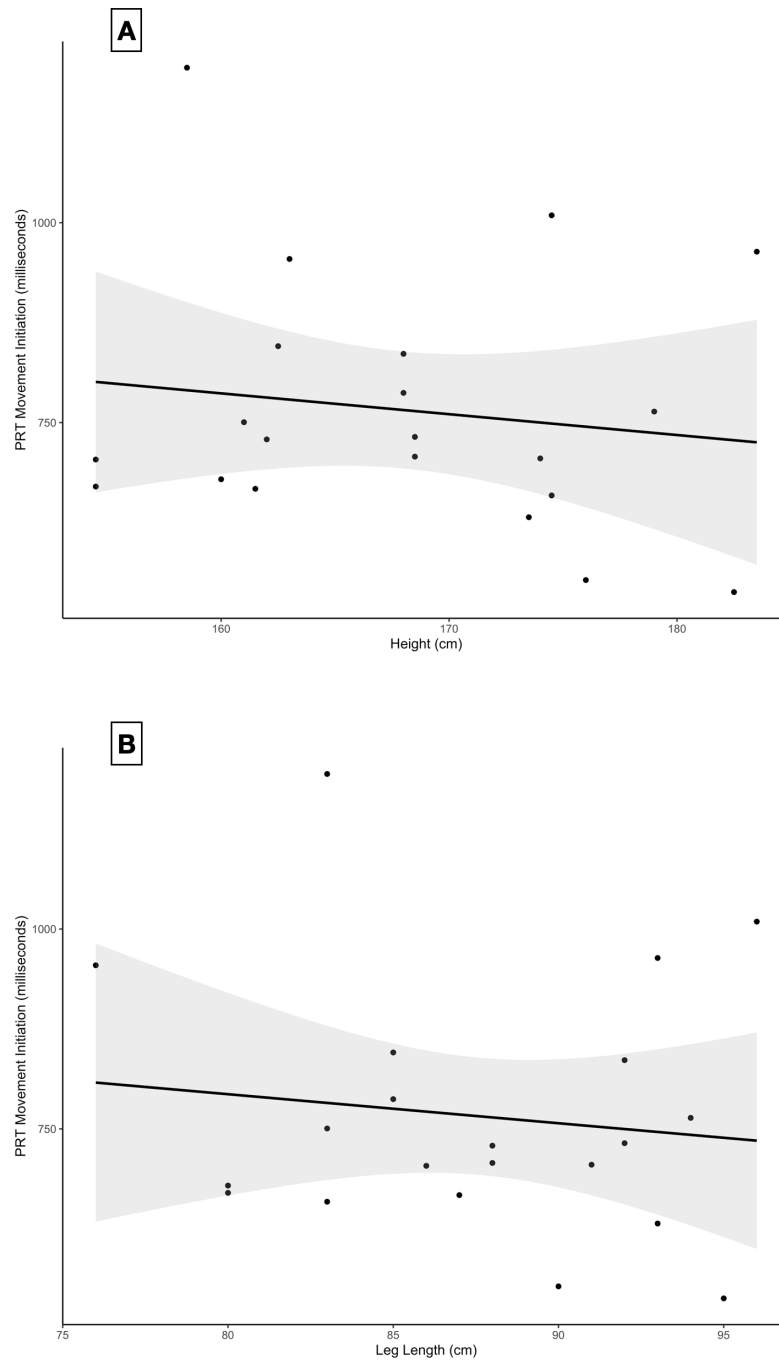


FIGURE 5.7: Linear models between PRT performance and subject anthropometry. A – depicts relationship with subject height. B – depicts relationship with true leg length measured according to (Gogia and Braatz [1986](#))

The effects of individual variability between batters can also be investigated. The

height, and particularly leg length of a batter, influences distance of nerve signal transmission and moment arm length for moving limbs. As a result, it can be hypothesized that taller batters may be disadvantaged in how rapidly signals presented at the central nervous system can be translated into appropriate lower-limb movement. In our investigation, leg-length was not correlated with PRT performance ($\beta = 0.00$, $p = 0.58$), suggesting no measurable effect in our sample. However, such an observation should be confirmed alongside batting protocols.

On sport performance, a similar device (Batak Lite test; (Gierczuk and Bujak 2014)) requires athletes to respond to visual stimuli presented arranged in an 'X' pattern of the 1.1m x 1.8m grid. (Gierczuk and Bujak 2014) claim that the device can be used to improve hand-eye coordination, reaction times and endurance. Veness et al. (2017) induced mental fatigue in elite cricket players and the mentally fatiguing condition did not negatively affect performance on the Batak Lite test. But other cricket specific performance measures (e.g., running between the wickets) were negatively affected (Veness et al. 2017). The PRT could be similarly used to assess mental fatigue or even provide an alternate means to induce mental fatigue compatible with batting.

Conclusion The accuracy of the PRT appears well correlated with measures obtained from high-speed video footage. The precision of measures may require calibration to reflect measurements from video footage, however, error is predictable and consistent, which indicates acute changes in response times can be reliably quantified. Although further validity studies of test-retest reliability are necessary. More pertinent, is the current lack of quantifiable measures of cognition which can be concurrently obtained with batting and the PRT appears a credible solution. Response time performance of novice PRT users appears inversely related to standardized, computer-based analogues which further suggests a stand-alone, cricket specific task may provide relevant and novel data to the sport. Future research should identify methods of replicating other affordances of batting behaviour to measure decision making speed from the primary motor actions of stroke play.

Disclosure statement

The authors report no conflicts of interest

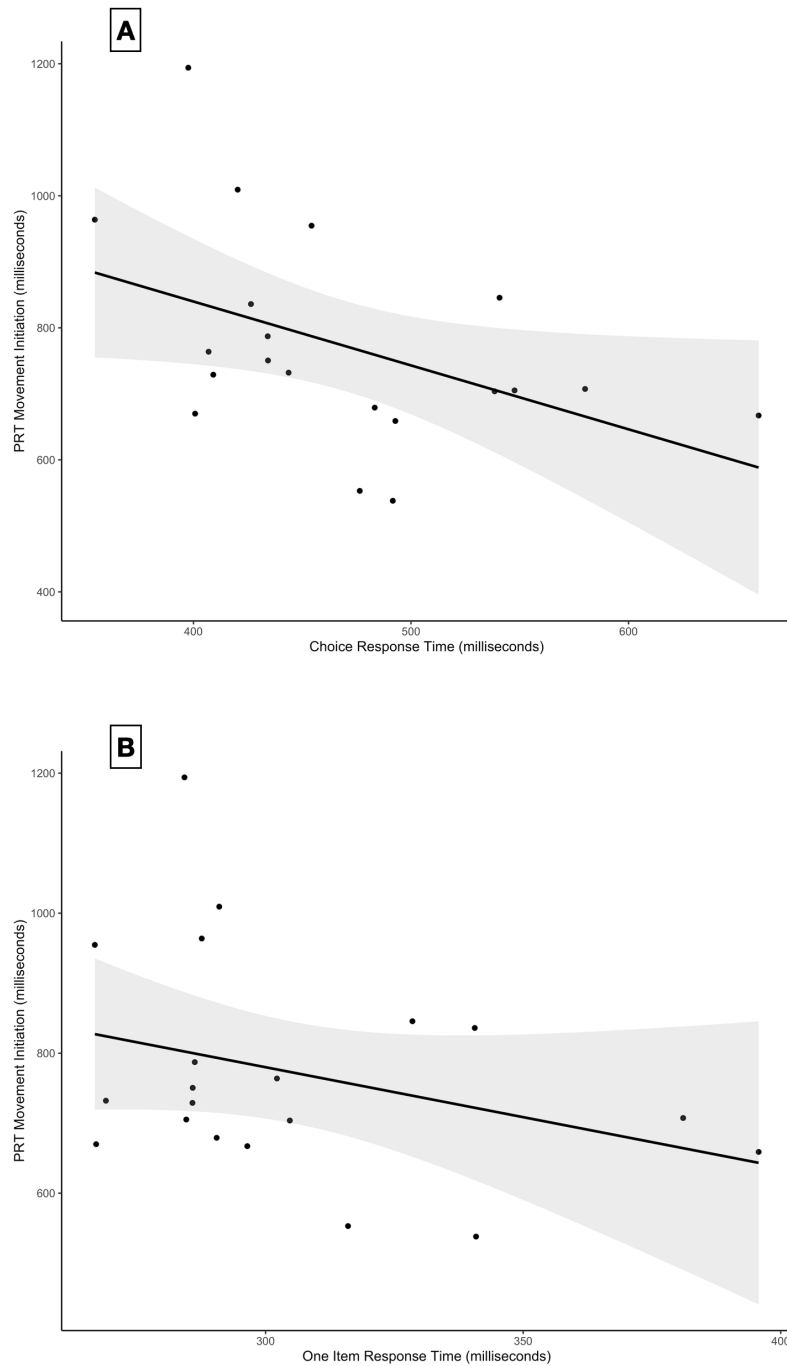


FIGURE 5.6: Linear models between PRT performance measured at the first sensory array and computer based analogue assessment (Psy-Toolkit). A – depicts relationship with choice response task consisting of four potential stimuli and four corresponding inputs. B – depicts relationship with single item task of one stimulus and one input

Chapter 6

Discussion

Presented in this thesis is a leading investigation of batting in Twenty20 cricket. First, the characteristics, duration, and undulations of run scoring in significant individual batting innings were replicated. The stochastic run outcomes of every delivery faced by batting pairs in professional matches were aggregated into two detailed innings simulations. The developed simulations produce equal partnership lengths (on-strike and off-strike deliveries), allowing the physiological determinants of run scoring intensity to be investigated – which previously was not possible.

In a sample of skilled batters, the physical strain of the high strike rate innings resulted in greater detriment to muscular output (sprint performance) and marginally higher heart rates than the low strike rate variant. However, sweat rate, lactate metabolism and incurred changes to peak power output were comparable between simulations. Cognitive performance showed a similar trend. Although, the short innings duration (1 hr 3 min) induced mild changes to cognitive functioning, the high strike rate innings resulted in a clearer emphasis on augmenting response times at the expense of executive functioning accuracy. Working memory response times improved across the board, but more errors in executive functioning ($d = 0.08$ vs $d = 0.60$) are observed following the high strike rate simulation. Finally, the cognitive findings motivated the need to measure cognitive performance from a task paradigm that is a closer analogue to the perceptual sensory-motor task of batting. A novel device that is deployed on a cricket pitch (Pitch Reaction Test) was developed to measure response times using an established task paradigm – choice responses to distinct stimuli. The PRT was evaluated in a laboratory study with healthy, young (< 30 years) participants. The accuracy of measurements from the device is promising but inconclusive when reviewed against slow-motion footage.

The aim of this chapter is to assimilate these results and contrast Twenty20 cricket to other formats of the game. The developed innings simulations and device for quantifying cricket-specific cognitive performance are novel, and logically collate for further discussion on practical applications in research and training environments. The

bi-directional effect of physical stress on cognitive function, and prolonged cognitive control on physical performance, is essential to batting performance and thus these variables must be linked.

6.1 Exercise-Cognition Interaction in Twenty20 Cricket

Taken together, the presented findings point to a moderating effect of strike rate on physical and cognitive performance. A key objective within the method of Chapter II was to impart strict control on the variable of innings duration. Or, from a physiological perspective, control the duration of whole-body physical activity. Leading models of the exercise-cognition interaction posit that cognitive functioning is most influenced by the duration of physical activity/stress (Dietrich and Audiffren [2011]; McMorris [2016]). Cognitive function deteriorates more significantly with prolonged activity. (Audiffren [2016]; McMorris [2021]). Dietrich and Audiffren ([2011]) describe that a compensatory mechanism of finite supply, is the divergence of neural resources towards cerebral structures involved in sustaining muscular contractions. Resultantly, the pre-frontal cortex (PFC) sacrifices metabolic priority (hypofrontality) but, similarly, must initiate compensatory mechanisms to sustain appropriate functioning (Dietrich and Audiffren [2011]; Audiffren [2016]). Ultimately the PFC will be susceptible to prolonged hypofrontality as compensatory mechanisms/resources deplete (Audiffren [2016]; Jung et al. [2022]). Therefore, two exercise conditions of equal duration will exert comparable costs to neural matter, unless an extreme difference in physical intensity (exhaustion vs leisure) is present (Audiffren [2016]; Jung et al. [2022]). For this purpose, the duration of the high and low strike rate innings simulations were matched to isolate a second explanatory variable – intensity.

Work achieved per unit of time (intensity) of physical activity effects the endocrinological stress response of the exerciser (McGuigan, Egan, and Foster [2004]). Increasing intensities impart greater demands on the rate of ATP production (Beneke, Leithäuser, and Ochental [2011]) and thus mobilisation of energy stores increases, via sympathetic innervation of the adrenal glands (Rabasa and Dickson [2016]). According to the catecholamine hypothesis, adrenal-derived catecholamines modulate the concentration of dopamine and epinephrine in the PFC, which modulates the exerciser's state of arousal (McMorris [2016]; McMorris, Barwood, and Corbett [2018]). The hypothesis predicts that intensity below the ventilatory threshold, facilitates arousal and cognitive functioning (Reviewed by Lambourne & Tomporowski Lambourne and Tomporowski ([2010]; McMorris & Hale McMorris and Hale ([2012])). While intensities which exceed the

exerciser's ventilatory threshold, cause excessive catecholamine secretion and neurotransmitter concentrations - impairing cognitive function (McMorris 2016). Therefore, exercise bouts of equal duration but differing intensity may produce contrasting cognitive outcomes (McMorris and Hale 2012; Jung et al. 2022). It may seem plausible that, experienced, skilled batters were sufficiently adapted to the physical demands of the low strike rate innings. Compared to measures at baseline, batters produced faster response times with comparable error-rates (4.1) after completing the innings. In contrast, an increased error-rate in executive functioning, suggests that the high strike rate innings imparts more physical intensity, causing more cognitive compensations (McMorris 2021; Jung et al. 2022). Distinguishable classes of intensity should be present between innings to conform with the catecholamine hypothesis, but the parameters of physical intensity measured in this study are marginally dissimilar.

Heart rate, a strong correlate of ventilatory thresholds (Cottin et al. 2006), is higher by $\beta = 5.4 \text{ beats} \cdot \text{min}^{-1}$ ($p < 0.01$) for the duration of the high strike rate innings. Figure 3.3 clarifies that heart rate measurements during the PowerPlay are most dissimilar, and converge at the latter overs/ phases. Thus, cardiovascular strain just prior to the second cognitive assessment is only $7 \text{ beats} \cdot \text{min}^{-1}$ (4.3%) higher in the high strike rate innings – statistically similar enough ($p = 0.58$) to doubt that differences in cognitive performance have an intensity-dependent culprit. Mean heart rates in the low and high strike rate Twenty20 simulations (148 and $153 \text{ beats} \cdot \text{min}^{-1}$) are also near identical to those previously reported in other centre-wicket simulations ($146 \text{ beats} \cdot \text{min}^{-1}$) and match play ($152 \text{ beats} \cdot \text{min}^{-1}$) (Vickery et al. 2018).

A second descriptor substantiates the similarities of physical intensity induced by both innings variants. Blood-lactate concentration defines the limit of oxidative/glycolytic cellular energy metabolism, and is therefore considered pivotal to the endocrine response of the exerciser (Rabasa and Dickson 2016). Batters produced comparable blood-lactate concentrations across both innings $f(1, 12) = 0.17, p = 0.67$ (Figure 3.1). In other words, the run scoring intensity of a Twenty20 innings may not significantly affect the physical intensity of the innings. In an innings simulation of the 50-over format, Houghton, Dawson, and Rubenson (2011) reported blood-lactate concentrations of $3.2 - 4.5 \text{ mmol} \cdot \text{L}^{-1}$ which is comparable to that seen in the low strike rate simulation $\beta = 2.8 - 4.4 \text{ mmol} \cdot \text{L}^{-1}$. A Twenty20 innings, however, may impart greater anaerobic demands as the latter phases of the high strike rate innings recorded increased blood-lactate concentrations ($\beta = 5.1 - 5.2 \text{ mmol} \cdot \text{L}^{-1}$) to those previously reported.

To our knowledge, no study has investigated the impact of striking rates on the batter, which appears to be a modifier of cognitive function and cricket-specific performance.

A supporting investigation which assessed the cognitive function of batters at multiple increments of an ODI batting simulation reported a time-dependant effect. As predicted by the RAH model (Dietrich and Audiffren [2011](#)), batters performed on par with their baseline assessments for the early measurements between 1-10 overs (Goble and Christie [2017](#)). Thereafter, deficits to executive function and working memory are reported with the most marked difference at the final assessment – near 4 hours of activity later (Goble and Christie [2017](#)). In our experiments, run scoring intensity appears to modulate the cognitive performance of batters in a fatiguing Twenty20 innings. Variables of physical intensity show little relation to the differences in cognitive variables but, the observed performance trend is conformative with the RAH model (Dietrich and Audiffren [2011](#)). Hypofrontality is predicted to not affect cognition homogenously. Instead, it is argued that cognitive domains which are surplus to needs during the extreme physiological stress of exercise will be downregulated (Dietrich and Audiffren [2011](#); Audiffren [2016](#)). While the cognitive domains responsible for reactive evaluations of ‘fight or flight’ will be heightened (Dietrich and Audiffren [2011](#); Audiffren [2016](#)).

Prolonged, high strike rate, Twenty20 batting hindered explicit processing streams, while implicit processing streams were accelerated with no increase in error-rate. Two categories/methods of stimuli computation are described in dual-processing theory (Evans and Stanovich [2013](#); Thompson [2013](#)). Explicit information processing is categorised as cognitive challenges which require the contents of working memory to be continually updated/refreshed according to internal and external goals (Baddeley [2012](#); Evans and Stanovich [2013](#)). Or, require that the contents of working memory are manipulated to imagine unforeseen stimuli/scenarios to plan responses for such circumstances (Baddeley [2012](#)). By contrast, implicit information processing operates without taxing working memory capacity (Evans and Stanovich [2013](#); D’Esposito and Postle [2015](#)). In other words, the outcome of the stimuli/task already has a neural representation which has been learned through practice (Furley, Schweizer, and Bertrams [2015](#)). When temporal constraints are high, implicit processing is favoured, as responses to availing stimuli require outputs which are already ‘pre-coded’ rather than imagined, manipulated and error-checked in real time (Yarrow, Brown, and Krakauer [2009](#); Furley, Schweizer, and Bertrams [2015](#)). Implicit processing is, therefore, believed to be dominant in sports, where faster responses are often desired (Yarrow, Brown, and Krakauer [2009](#)).

In the RAH model, it is postulated that explicit information processing streams are hierarchically downregulated depending on the severity of resource restriction in PFC

(Dietrich and Audiffren 2011). That is, cognitive efficiency will first be lost at highest-order executive functions while tasks which require progressively less working memory input remain intact (Audiffren 2016; Jung et al. 2022). Resultantly, the joint effects of exercise-induced arousal and hypofrontality further shift cognitive priority towards implicit information processing (McMorris 2016) while explicit processing is progressively impaired (Audiffren 2016). An intriguing finding presented in this thesis is that the differing cognitive outcomes are not convincingly explained by intensity nor duration. Further, the cognitive findings demonstrate that in one scenario ('high' strike rate batting), the PFC can be sufficiently compromised in explicit processing efficiency. While implicit processing is upregulated, showing better efficiency (Figure 4.1) than 'low' strike rate batting – where explicit processing accuracy remained intact.

The haemodynamic response of the PFC confirms a divergence between innings variants. The cognitive assessments performed prior and following both innings are equivalent cognitive challenges and therefore differences in PFC substrate metabolism can be related to the stress met in interim of assessments. Batters displayed higher oxygenated haemoglobin concentrations (HBO) following the low strike rate innings. While higher deoxygenated haemoglobin concentrations (HBR) are observed following the high strike rate innings (Figure 4.2). Increased HBO following the low strike rate innings is indicative of greater cerebral activation (Scholkmann et al. 2014) in the assessment compared to the high strike rate variant. The increased activation can be critiqued as the result of experienced batters being accustomed to the physical demands of batting at lower strike rates, therefore sufficient substrate reserve is available following the innings (Giles et al. 2014). Another interpretation is that batting at high strike rates requires considerable PFC activation, and therefore no further increases are achieved at the post-batting cognitive assessment.

fNIR spectroscopy measures changes in HBO and HBR continuously compared to the concentration/signal measured at a baseline – obtained in our study while batters sat quietly, observing a blank computer screen (Ferrari and Quaresima 2012). Before batting, cognitive challenges produce an expected increase in PFC activation (HBO) compared to the activation of quiet sitting (Figure 4.2) (Scholkmann et al. 2014). Hence, when batters perform the post-batting cognitive assessment and baseline is recalculated, it is plausible that activation cannot increase further when cognitive challenges are presented (Moriarty et al. 2019). Contrary to this, the RAH model would suggest that more hypofrontality (less HBO) is visibly (Figure 4.2) induced by the high strike rate innings and thus the differences in cognitive functioning are also predicted. The increased activation following the low strike rate innings then, is consistent with a

physical task which does not deplete neural resources of the PFC, and hence executive functioning is preserved (Figure 4.2, Table 4.1) (Audiffren 2016).

At the cessation of exercise, a drastic reduction in recruitment of neural matter which coordinates movement (pre-motor, motor cortex, cerebellum etc), results in a sudden increase of resource availability for the PFC (Secher, Seifert, and Van Lieshout 2008; Crush and Loprinzi 2017). Thus, the concentration of HBO in the PFC is expected to quickly return to ‘normal’ once batters are seated to perform the second cognitive assessment (Audiffren 2016). Numerous studies have reported a time-dependent effect when evaluating cognitive function after exercise (Crush and Loprinzi 2017; Frith, Sng, and Loprinzi 2017; McMorris and Hale 2012; Ishihara et al. 2021). Therefore, it is important to note that the PFC topographs in Figure 4.2 depict values averaged across the entirety of the 10–12-minute cognitive assessment. Although statistical analyses of PFC haemodynamics were not possible in this study (discussed later), overall, neural activity is distinguishable between innings and supported by cognitive outputs.

Taken together, it can be argued that batting at higher strike rates increases the degree of hypofrontality experienced by the batter. The high strike rate innings appears to prolong decreased PFC activation (Figure 4.2) and the predicted cognitive consequences of hypofrontality are present (Table 4.1). The Groton-Maze Task (GMT) provides a clear example of opposing neural activation patterns with discrepant task proficiencies. The rationale of this task is spatial learning of a maze hidden beneath a 10x10 grid, revealed one tile at a time. The GMT evaluates the batter’s ability to error-monitor while progressing through the maze, continually updating the contents of working memory to align with an external goal – the maze ending point (Pietrzak et al. 2008).

Goal-directed attention (Gazzaley and Nobre 2012; Oberauer 2019), the function of selecting and monitoring which stimuli enter the contents of working memory, is associated with activity in the ventrolateral PFC (Wager and Smith 2003; Rottschy et al. 2012). While activity at the dorsolateral PFC is linked with the maintenance (delay interval spiking) and manipulation of these contents (D’Esposito and Postle 2015; Eriksson et al. 2015; Miller, Lundqvist, and Bastos 2018). Hence, following the low strike rate innings, batters display more ventrolateral PFC activation (Figure 4.2) compared to the high strike variant. Moreover, high strike rate batting increased ventrolateral HBR concentrations, which supports the idea that the PFC is operating in a distinct metabolic window where implicit processing (void of working memory input) is favoured (Giles et al. 2014; Bediz et al. 2016). There is still little intuition however, according to the RAH model, for how this substantial difference in hypofrontality arises.

The executive control and allocation of attentional mechanisms (Engle [2018]; Oberauer [2019]), known to be sensitive to hypofrontality (Audiffren [2016]), may instead provide more insight. That is, as the exerciser's perception of physical strain and effort increases, attentional mechanisms will be unavoidably diverted towards this perception (Gazzaley and Nobre [2012]; McMorris [2021]). Hence, finite attentional resources are not adequately allocated to internal/external goals (Young and Stanton [2002]; Engle [2018]). Hindering the contents and maintenance of working memory, and ultimately explicit processing efficiency (Furley, Schweizer, and Bertrams [2015]).

In our study, ratings of perceived exertion (RPE) were minimally dissimilar between simulations but, there is evidence of a performance interaction. Batters perceived no distinguishable difference in cardiovascular strain between innings ($\beta = -0.3 \text{ points}$, $p = 0.43$). But the high strike rate simulation was perceived to be marginally more strenuous ($\beta = 0.6$, $\text{points } p = 0.049$) to lower-limb musculature. Batters also perceived local RPE to exceed central RPE by 7.1% on the Borg scale ($\beta = 0.9 \text{ points}$ ($p < 0.001$), in the high strike rate simulation, while both measures were interchangeable during the low strike rate variant ($\beta = 0.04$, $\text{points } p = 0.891$). The increased perception of lower-limb strain is accompanied by reduced muscular output. The high strike rate simulation recorded slower sprint times overall ($\beta = 0.10 \text{ seconds}$, $p < 0.01$ for on-strike runs; $\beta = 0.05 \text{ seconds}$, $p < 0.01$ for off-strike runs), and less deterioration to sprint times as the innings progressed (Figure [3.2]). Batters were naïve to the differences between simulations and therefore a negative relationship between perception of exertion and performance is noteworthy.

In Chapter 3, we posit that batting technique at high strike rates negatively affects sprint performance. To increase the likelihood of scoring boundaries, batters aim to maximise the kinematic forces at the collision between bat face and ball by increasing bat velocity (Peploe et al. [2019]). The batter adopts postures suited to applying maximal force on the lever of the bat and maintaining balance against the inertia of the accelerating mass (Peploe et al. [2019]). Therefore, the acceleratory strides of the sprint may be compromised by biomechanically unfavourable starting positions/leverages (Peploe et al. [2019]). A caveat to this explanation is that timing gates were placed 2.5m in front of the batter. Thus, the initial, slowest strides, where the batter transitions from stroke-sprint are not measured.

The lack of deterioration to sprint performance as the innings progressed, as seen in the low strike rate simulation (Figure [3.2]), suggests that batters employed preservative, self-regulatory control of their sprint performance. Indeed, Christie and colleagues Christie et al. ([2018]) reported that experienced batters apply superior pacing strategies

than their less-experienced counterparts. To avoid fatiguing prematurely, experienced batters weigh afferent feedback from exercising muscles with the stimuli from the playing environment to gauge how best to distribute effort throughout an innings (Christie et al. [2018]; Venhorst, Micklewright, and Noakes [2017]). For example, several boundaries have been scored and the batter perceives the early ‘PowerPlay’ phase of the innings to be physically intense. By gauging the playing environment, it is perceived that run scoring performance is satisfactory while physical exertion is perceived to be unsustainable – thus experienced batters may restrain physical outputs to maintain and prolong batting performance (Venhorst, Micklewright, and Noakes [2017]).

The relationship between perception of exertion and physical performance, particularly the limiting factors of performance, is described by central governor theory (Noakes, Peltonen, and Rusko [2001]; Noakes [2012]). In short, it is theorised that a central mediator in the brain protects cardiac tissue from catastrophic ischemia by limiting efferent output to exercising muscles before the physiological limits of energetics are approached (Noakes [2012]; Venhorst, Micklewright, and Noakes [2017]). Further evidence of batters moderating efferent output during an innings, is shown in lower-limb peak power output, which was assessed before and after batting.

Maximal vertical jump performance was comparable across both innings and measurement periods (Table [3.3]). The repeated maximal accelerations of running between the wickets is known to alter muscular structure (Pull and Ranson [2007]) and reduce peak power output associated with fatigue (Christie et al. [2019]). Therefore, batters may mask the true physical workload of an innings, by modulating their physical outputs to match an exertion ‘template’ honed over the experience of many innings’ (Edwards and Polman [2013]; Venhorst, Micklewright, and Noakes [2017]). Furthermore, the preservation of peak power output, combined with little-to no deterioration of prolonged sprint performance, and no single measurement of maximum RPE (highest reported RPE = 18), confirms that batters operated within their physical limits. Contrariwise, batters at their physical limits, muscular outputs drastically reduced, and blaring perceived exertions have likely forfeited cognitive and batting performance entirely. Skilled batters, as seen in our sample, are well-conditioned to the physicality of Twenty20 batting and manage their exertion throughout an innings for optimised batting performance (Christie et al. [2018]; Venhorst, Micklewright, and Noakes [2017]). Our findings suggests that cognitive exertion must form part of this computation (McMorris [2021]). That is, central governor activity computes an efferent output which leaves sufficient cognitive capacity to maximise batting performance.

Veness et al. (2017) provide a perspective of this modulation from an opposing methodology. Cricket-specific performance assessments were conducted on skilled batters after a control or mentally fatiguing condition in a randomised cross-over design. Mental fatigue was induced using a continuous response inhibition test (Stroop task) lasting 30-minutes while the control condition required batters to read leisurely for the same amount of time. Cognitive performance declined from the midway point of the mentally fatiguing conditions, and thereafter muscular output and aerobic performance was hindered (Veness et al. 2017). Batters also reported increased perceived exertions during physical assessments in the mentally fatigued condition (Veness et al. 2017). In our study, the high strike rate innings resulted in reduced sprint performance, but increased perceived exertion compared to the low strike rate variant. According to centrally mediated fatigue models (Venhorst, Micklewright, and Noakes 2017; McMorris 2021), it is conceivable that due to increased cognitive exertion, efferent output is restrained in the high strike rate innings to keep a targeted/expected level of exertion. This is achieved by learning states of physical and cognitive exertion which are tolerable to batting performance. And, how to strategically conserve effort in an innings for latter gains in batting performance – a template RPE (Edwards and Polman 2013; Venhorst, Micklewright, and Noakes 2017).

It is important then, to reiterate the collective physiological demands of Twenty20 batting – prolonged cognitive control with physical effort. Few studies have overcome the methodological difficulties of assessing cognitive function simultaneously with whole-body exercise and therefore data predominantly describes the acute relationship between exercise initiation/cessation and cognitive function (Brisswalter, Collardeau, and René 2002; Loprinzi and Lovorn 2019). Further, intermittent activity with periods of high physical intensity, such as Twenty20 batting evidenced in our study and prior (Sholto-Douglas et al. 2020), is the least studied exercise modality (Lambourne and Tomporowski 2010; Loprinzi and Lovorn 2019). We posit that the rate of run scoring may have less impact on the physical workload of a Twenty20 innings, the cognitive intensity however, is ramped. Batting at increasing strike rates demands an increased frequency of faultless, boundary-worthy ball interceptions (Peplow et al. 2018). Batters aim to increase the kinematic forces at interception and exerting more force may pose cognitive consequences.

First, there is benefit to accelerating the selection of relevant motor responses from earlier, and fewer availing stimuli in the bowler's action and ball flight (Sarpeshkar and Mann 2011). Stricter temporal constraint on response selection, alleviates time for force application, and therefore the bat can accumulate more kinetic energy before

impact (Sarpeshkar and Mann 2011). Earlier and increased force application will also enable the bat-swing to advance through more degrees of ‘downswing’, returning to an upward arc, imparting more vertical velocity and distance/carry (Peploe et al. 2019; Noorbhai 2020a). Second, increasing force output recruits more motor-neurons (Del Vecchio et al. 2019) which augments the computational load of coordinating movement (Dietrich and Audiffren 2011) while the resultant high-speed mass leaves little margin for error/correction (Sarpeshkar and Mann 2011). Thus, motor responses of increased force and motor-neuron recruitment are computed in less time (Del Vecchio et al. 2019).

The high strike rate innings caused batters to be quicker in response but with increased error-rates – indicative of suppressed executive processing (McMorris and Hale 2012; Ishihara et al. 2021). While increased concentrations of deoxygenated haemoglobin in the PFC (Figure 4.2) confirm there are metabolic limitations, and therefore compensations present. One compensation as predicted by the RAH model – hypofrontality promotes hierarchical downregulation of explicit/executive processing and upregulation of implicit streams (Dietrich and Audiffren 2011; Audiffren 2016). Another compensation will be based on a central mediator computing variables of exertion against previous experience to solve for optimal batting performance (Christie et al. 2018; McMorris 2021).

In other words, skilled batters may subconsciously learn that if the cognitive demands of high strike rate batting cannot be met – batting performance is unwillingly sacrificed (Venhorst, Micklewright, and Noakes 2017). Therefore, to safeguard strained cognitive systems from further stress (hypofrontality, perceived exertion) assaults (Audiffren 2016), efferent/muscular output is subconsciously dampened (Zering et al. 2017; Venhorst, Micklewright, and Noakes 2017). In the high strike rate innings, the burden of required boundaries is instated from the first over and resultantly batters may be cognitively exerted and fatiguing prematurely. Lower-limb muscular output is reduced (Figure 3.2), although cardiovascular strain is increased (Figure 3.3), as outputs are collectively managed for a performance equilibrium (Venhorst, Micklewright, and Noakes 2017; Brown et al. 2020). It may be that high strike rate batting increases the computational costs of ball-striking, and therefore requires increased executive control of exertion (Veness et al. 2017; McMorris 2021) which alters cognitive functioning and PFC haemodynamics of skilled batters.

6.2 Practical Implications and Future Research

The physiological responses of skilled batters during an innings may be ambiguous. Particularly, a batter's reported physical exertion can be influenced by cognitive workloads (Goble and Christie [2017](#); Veness et al. [2017](#)) and variables of physical/muscular performance may be disguised by habitual pacing strategies (Christie et al. [2018](#)). Hence, physiological variables of prolonged responses to a batting innings should be interpreted holistically. Data presented in this thesis, when considered with broader literature, suggests that the determinants of run scoring rate may be more cognitive than physical. The physical stress of a Twenty20 innings will unavoidably alter the batter's state of arousal (Dietrich and Audiffren [2011](#); McMorris [2016](#)). Theoretically improving ball-striking competency from augmented implicit processing of sensory-motor couples (Furley, Schweizer, and Bertrams [2015](#)). Cognitive deficits can be incurred however, as we have shown, when the combined cognitive and physical workload exceeds tolerance (Zering et al. [2017](#)). In a standardised computer assessment, skilled batters displayed suppressed executive functioning following high strike rate batting. The true effect of reduced executive functioning can only be speculated until future research expands on the neural and cognitive correlates of batting performance.

It is widely accepted that extreme temporal constraints override executive processing by default, for quicker, implicit responses (Yarrow, Brown, and Krakauer [2009](#); Furley, Schweizer, and Bertrams [2015](#)). Plainly, batters are not consciously aware of the decision-making processes of ball-striking, instead motor responses are coupled to a particular set of stimuli for faster response execution (Furley, Schweizer, and Bertrams [2015](#)). The process of learning and repetition fortifies the sensory-motor couples (Rolfs and Schweitzer [2022](#)) and therefore when akin sets of stimuli arise, motor responses can be autonomously initiated with limited central executive and working memory input (Baddeley [2012](#)). A batter's ability to intercept deliveries may be theoretically robust to hypofrontality. It would be premature however, to conclude that batting performance is not negatively affected by suppressed executive functioning. Furley, Schweizer, and Bertrams ([2015](#)) describe that working memory involvement exists on a continuum rather than an all-or-nothing input. Therefore, it is conceivable that when skilled batters perceive kinematic cues in the bowler's action (Brenton, Müller, and Harbaugh [2019](#)), these cues will be maintained in working memory to be evaluated with 'live' stimuli of ball-flight (Sarpeshkar and Mann [2011](#); Furley, Schweizer, and Bertrams [2015](#)). If executive function is suppressed, the visuospatial sequence maintained in working memory may be of reduced duration/detail (Baddeley [2012](#); Rolfs and Schweitzer [2022](#)), but empirically supporting data is methodologically challenging

to obtain.

In a prolonged Twenty20 innings, the interim between deliveries within an over, and between overs, provides opportunity for strategising i.e., executive functioning (Fuster 2013). The time frame of information processing amplifies to 15 seconds between deliveries, and 50 seconds between overs (Chapter II; Houghton, Dawson, and Rubenson 2011), supporting explicit processing of internal and external stimuli (Fuster 2013). The contents of working memory, monitored by central executive oversight, bias perception of live stimuli by guiding attentional mechanisms (Gazzaley and Nobre 2012; Engle 2018). Hence, explicit processing of match stimuli aids the batter's anticipation of upcoming deliveries (Müller, Brenton, and O'Grady 2023).

For example, a bowler is permitted one delivery per over which can bounce above shoulder-height of the batter (ICC 2021). If the first delivery of an over is above shoulder-height and signalled by the umpire, the batter becomes aware of a restricted criterion of legal deliveries. The batter may consider that the given bowler will not risk awarding penalty runs (extras) to the opposition, suggesting remaining deliveries of the over will be well-below shoulder height. Therefore, the number of potential responding strokes has reduced. This perception involves the central executive and a component of working memory (the visual-spatial sketchpad) to heighten attentional mechanisms to the appearance of a subset criterion of visual stimuli – biasing perception (Corbetta and Shulman 2002; Engle 2018). A competitive advantage is presented if match stimuli can be effectively reasoned, and our results suggest skilled batters are more susceptible to errors in planning/reasoning at high striking rates. However, reduced executive performance observed in the Groton-maze task is not easily related to deficits in batting performance.

In Chapter V, we propose a methodological paradigm and device which can be used to quantify perceptual-motor performance specific to batting. The cognitive processes of batting are the result of a performer-environment interaction, and therefore batting-related cognitive efficiencies cannot be accurately deduced if this interaction is voided (Araújo, Davids, et al. 2009; Duarte Araújo and Davids 2019). Several studies, including those presented in this thesis, measure acute changes in cognitive functioning of the performer, but are limited by assessments which are not designed to replicate the sporting environment (Reviewed by (Dong et al. 2022)). Standardised cognitive assessments, like the CogState test battery (Maruff et al. 2009), require performers to be removed from the competitive environment and assessed while seated. The interactions of participant, stimuli and output/decision are validated to measure the efficiency

of cognitive parameters without mental processes that are involved in batting. Further, when participants are assessed in a seated posture, transient changes in cognitive functioning can be masked by physiological recovery (Lambourne and Tomporowski 2010; Crush and Loprinzi 2017). Potential limiters of batting performance related to the exercise-cognition interaction should therefore be gleaned during competition. Or, from assessments that mimic the environment and affordances (stimuli) of match play (Duarte Araújo and Davids 2019).

The Pitch Reaction Test (PRT) quantifies psychomotor function by detecting the user/batters' responsive foot-movements. Conducted on a cricket pitch, the PRT analogues a choice response task paradigm (Brown and Heathcote 2008; Deary, Liewald, and Nissan 2011), but choices/responses are familiar movements of stroke-play. The two-choice stimuli are positioned along the length of the pitch, representing where upcoming deliveries may bounce before reaching the batter. Hence, the batter's action is to promptly adopt a balanced position to execute a responding stroke. Although the availing stimuli presented by the PRT are not exact analogues of the visual stimuli computed while batting. A more specific coupling of perception (identifying the 'length' of a delivery) with learned actions (shifting weight onto the 'front' or 'back foot') provides measurements that can be more readily related ball-striking and batting performance (Duarte Araújo and Davids 2019).

Psychomotor performance is requisite in an interceptive task, where movement is coordinated from the integration of visual stimuli (Sarpeshkar and Mann 2011). Innovations like the PRT specialise the perception-action characteristics of cognitive assessments to sacrifice generalisability, for a measure of Sport Specific Psychomotor Performance (SSPP) (Habay et al. 2021). Redesigning task paradigms for sport specific applications also enables cognitive function to be assessed homogeneously during match play or simulations of match play. Batting specific psychomotor performance can therefore be measured longitudinally (e.g., at the cessation of every over) with less disruption to a batter completing an innings. Importantly, the predicted cognitive trade-offs, of heightened implicit processing at the expense of executive control, can be empirically investigated in a batting context.

The task paradigm of the PRT limits the involvement of working memory and central executive oversight, by limiting stimuli-response permutations (Brown and Heathcote 2008; Deary, Liewald, and Nissan 2011). The low number of response permutations allows each perception-action couple to be represented in a working memory attentional set, where responses form part of the user/batter's cognitive representation of the task

(Corbetta and Shulman [2002]; Fajen, Riley, and Turvey [2008]). Resultantly, novel responses do not need to be computed to availing stimuli and implicit function (speed of processing) is emphasised (Furley, Schweizer, and Bertrams [2015]; Engle [2018]). Longitudinal PRT assessments throughout an innings can therefore corroborate how physical stress and reticular-activation (arousal) influences the batters' response latency to familiar stimuli (McMorris [2016]; Engle [2018]). Further batting specific hypotheses of the RAH model can be assessed by reintroducing working memory demands to the PRT.

As previously discussed (Chapter V), a stop-signal task paradigm (Verbruggen and Logan [2008]; Congdon et al. [2012]) can also be adapted to the PRT to quantify errors of executive/inhibitory control. First, by introducing an additional stimuli-response permutation, the cognitive representation of the task maintained in working memory expands (Fajen, Riley, and Turvey [2008]; Thompson [2013]). Thus, greater executive control is required to monitor these representations, and to inhibit unwanted responses (Baddeley [2012]; Gazzaley and Nobre [2012]). Response inhibition efficiency can then be related to batting performance. For example, if the physical stress and resultant hypofrontality diminishes a batters' executive control (Dietrich and Audiffren [2011]) - increased error-rates should be observed in PRT responses/assessments. Psychomotor errors caused by mimicking stimuli means batters are *moving* inappropriately, or prematurely to availing stimuli. It can then be argued that the consequences of hypofrontality may leave batters vulnerable to deliveries with discrepant trajectories/deviations, produced from similar kinematic signatures (mimicking stimuli) in the bowling action. An added cognitive variable can be assessed from the PRT by requiring the user/batter's responsive inputs to be altered when triggers/signals are met.

Set, describes the executive function of preparing neural resources for improved efficiency based on the anticipation of sensory inputs (Stemme, Deco, and Busch [2007]). In the batting context, attentional resources are *set* based on perception of the performance environment and memory (Fuster [2013]). That is, a batter perceives a right-arm medium-fast bowler, and based on recent and long-term memories, sensory-motor couples are prepared for enhanced efficiency (Corbetta and Shulman [2002]; Yarrow, Brown, and Krakauer [2009]). The ability to update attentive sets (set-shifting), requires prepared neural resources to be reconfigured for efficiency when new conditions or rules are presented (Stemme, Deco, and Busch [2007]). Likewise, when a new bowler is introduced to the attack, the batter must update perceptual and motor sets to suit. Or, the batter's recent memory of preceding deliveries, and perception of difficult playing conditions - reveals that a given motor response/stroke is inherently risky. Hence,

perception-action coupling should be malleable to bias or dampen (set) responses (Corbetta and Shulman [2002]) according to the batter's evolving cognitive representation of the game/innings. Set-shifting efficiency is expected to be particularly sensitive to hypofrontality (Dietrich and Audiffren [2011]; Jung et al. [2022]) which is especially relevant in the fast-paced Twenty20 format where environmental affordances (bowling and fielding changes) will be most frenzied.

A set-shifting task paradigm (Stemme, Deco, and Busch [2007]; Eling, Derckx, and Maes [2008]) can be adapted to the PRT by methodically inverting the stimuli-action regulations of the task. The standard regulation entails that stimuli near the subject/batter are responded to with a forward lunge. While stimuli at the distal end of the wicket are responded to with a backward lunge. A set-shifting event/cue would indicate that the subject must inverse responses for subsequent trials – i.e., distal signals require a forward lunge. The rationale being to engage working memory - which must maintain an updated cognitive representation of the current perception-action couple (Furley and Memmert [2010]). And central executive oversight of the contents of working memory, to appropriately reject outdated cognitive representations and their interference (Rolfes and Schweitzer [2022]). Once habituated, subjects can naïvely encounter set-shifting cues during a PRT assessment - highlighting the efficiency of executive functions with psychomotor consequences that can be related to batting. Future research should continue to investigate and validate task paradigms which emphasise cognitive parameters that can be related to the specific performer-environment interaction seen in cricket (Duarte Araújo and Davids [2019]).

Preparing for a competitive Twenty20 batting innings is multifaceted. Not only should batters be physically prepared (Scanlan et al. [2016]), but cognitive exertion is also shown to influence batting performance (Veness et al. [2017]). For skill development, it is therefore important that batters are exposed to the combined cognitive and physical stressors of an innings (Pinder et al. [2011]). Training regimes however, often do not conform to prioritising combined stressors of match play, from youth to elite samples (Goble and Christie [2017]; Vickery et al. [2018]). Vickery et al. ([2018]) reported that conditioning exercises prescribed to national level batters exceeded the physical demands of match play, and were also performed separately from technical batting sessions. Technical sessions included centre-wicket simulations but traditional net based training was most frequent (Vickery et al. [2018]). Such training modalities, where the interception of deliveries is not coupled with appropriate physical stress and the dynamics of a progressing innings/match, disregard pertinent stressors and limiters of batting performance. Instead, batters should be routinely exposed to batting with

modulated cognitive efficiencies caused by exertion and fatigue that is most representative of match play (Pinder et al. 2011).

Innings simulations supply much needed methods of replicating the stressor combinations of a competitive innings. Put simply, skill development and learning is facilitated when training is representative of the performance environment (Pinder et al. 2011; Davids et al. 2013). The environment of a competitive Twenty20 innings entails a strict restriction to number of deliveries faced from several bowlers in rotation, and malleable fielding positions. Batters must therefore act on run scoring opportunities/affordances which are not presented uniformly in a prolonged innings. In a simulated innings, the physical consequences of run scoring are dictated and therefore batters perform under suitable states of exertion and fatigue. Further ecological dynamics of a Twenty20 innings can also be replicated, such as fluctuating run scoring rates, varying run scoring zones and ramping performance requirements. Thus, batters are exposed to relevant stressor combinations and adaptations that are more transferable to batting performance in the competitive environment can be learned (Woods et al. 2020).

Run scoring performance may therefore be developed irrespective of advances in technical ball-striking ability. Incorporating innings simulations in a training regimen enables batters to learn individual, pragmatic solutions to manage run scoring throughout an innings (Pinder et al. 2011; Woods et al. 2020). According to our results, a practical hypothesis for batting performance would be to alleviate, as far as possible, the burden of intra-innings strategising/planning. That is, rather than evaluating an undefined number of match stimuli at unknown intervals. Batters may instead benefit from performing conditional evaluations with specific, practised responses to given conditions. For example, off-spin bowled from around the wicket in the final ‘x’ overs of an innings, permits the batter take guard on off-stump, emphasising a boundary scoring stroke for any delivery pitching in line with the stumps.

Several ecological cues of bowlers changing angle of attack, or fielders moving to different catching positions can be embedded in training simulations. Responsive strategies can then be tailored to individual strengths/weaknesses. Or, to prepare for specific tactics employed by the opposing team. In the training environment, batters can be challenged with several ecologically relevant cues, which inform adjustments to batting behaviour for niche tactical run-scoring advantages. The evaluation of these cues and subsequent updates to batting strategy can occur under appropriate stress - enhancing learning and skill transfer to competition (Pinder et al. 2011; Woods et al. 2020). Defining which conditions/stimuli are evaluated at given intervals allows batters to

scan familiar groups of stimuli, repeatedly during training. Resultantly, these evaluations of match stimuli can form part of the batter's learned cognitive representations of an innings. Enabling tactical responses to be implicitly processed when familiar conditions are encountered in the competitive environment (Furley, Schweizer, and Bertrams 2015). Theoretically then, attentional mechanisms can be tactfully guided with less central executive oversight – minimising an aspect of cognitive workload and potential errors associated with hypofrontality (Ishihara et al. 2021; Jung et al. 2022). With attentional mechanisms guided to fewer stimuli and motor-responses tactfully pre-empted - implicit sensory-motor performance and ultimately run scoring aptitude is facilitated (Furley, Schweizer, and Bertrams 2015). How batters of different skill-levels utilise match stimuli for anticipatory ball-striking advantages should be further investigated (Müller, Brenton, and O'Grady 2023).

6.3 Critical Reflection and Limitations

Like this thesis, several batting studies have been limited by using standardised cognitive assessments to infer performance changes specific to a performer-environment interaction (Goble and Christie 2017; Veness et al. 2017). Although Chapter V attempts to remedy this gap in literature, some critiques are necessary. First, the device is not a complete representation of the affordances computed by a batter in competition. Perception-action coupling of the PRT is significantly simplified compared to that of intercepting a high velocity cricket ball. Therefore, results are representative of a subset of cognitive correlates of batting with an undetermined extent of true overlap. Verifying the measuring accuracy of the device also proves challenging. The method employed in this study compared measurements from the PRT to a 'gold standard' which was limited to 240 still frames per second. Arguably a device which computes measurements to within 10 milliseconds should be validated against comparably sensitive measures.

Improved lighting and cameras would allow frame rates to be increased beyond 1000 frames per second. However, labelling a still frame based on characteristics of foot movement may be subjective between raters, creating another margin of error. A more binary definition can be achieved instead, by closely observing the sensory array and labelling the moment/frame that light from the laser array makes/breaks contact. Regardless, measurements analysed in Chapter V show that the developed hardware and software computes response times that are strongly correlated with reality (Figure 5.4). For the intended purpose of monitoring cognitive function throughout a batting intervention, test-retest reliability within an individual is equally important to the

exact precision of measurements (Polit [2014](#)). That is, the individual variability of PRT performance in separate assessments. Before acute changes in performance can be accurately deduced from the PRT, it would be necessary to study learning curves and variability of re-test performance at different intervals – hours, days, weeks (Polit [2014](#)). Such an assessment was beyond the scope of this thesis.

fNIR spectroscopy measures of the prefrontal cortex could not be subjected to the initially desired statistical scrutiny. Raw data from most post-batting assessments did not withstand recommended processing and filtering constricting the sample to $n = 5$. A possible explanation for the rejected data is the physiological artifacts of exercise and post-exercise recovery. fNIRS reduce technological and logistical barriers of PET or fMRI techniques (Ferrari and Quaresima [2012](#)), but other limitations are presented. Computing neural substrate utilisation from the refraction and reflection of light through the forehead, means cerebral blood flow must be isolated from cranial interference (Scholkmann et al. [2014](#)). fNIRS measurements conducted after a batting innings assess the recovery period of a high-intensity exercise bout. Hence, respiratory frequency and cranial haemodynamics are not constant for the period of assessment - creating a form of physiological noise (Scholkmann et al. [2014](#)). In previous studies, fNIRS measurements were obtained after 5–15-minutes of recovery from light-moderate intensity activity (Giles et al. [2014](#); Moriarty et al. [2019](#)). A caveat to delaying assessments is that the most acute exercise-cognition interaction is omitted, and therefore the neural determinants of batting performance remain unstudied.

In hindsight, complimentary variables could have been collected in tandem with fNIRS measurements. Heart rate variability (HRV), respiratory frequency and tidal volume are beneficial for filtering physiological artefacts from raw spectroscopy data (Ferrari and Quaresima [2012](#); Scholkmann et al. [2014](#)). These measures also describe autonomic nervous system activity (vagal tone), providing more context to the subject's cognitive workload and performance (Laborde, Mosley, and Thayer [2017](#)). The experimental design should assess the PFC haemodynamics of batters completing a cognitively demanding tasks before and after batting conditions/interventions. A baseline measure before the cognitive challenge is obtained from batters standing, observing the playing environment. Thereafter, post-batting measures are recorded at standardised physiological waypoints – for example post-batting assessments are initiated when respiratory frequency and heart rate are similar to baseline. Time elapsed for individual recovery to baseline can be recorded to correlate physical fitness (cardiovascular recovery) with cognitive parameters in the assessment. While continuously measuring HRV can be used to describe states of acute mental stress (Castaldo et al. [2015](#)) and autonomic

regulation (Laborde, Mosley, and Thayer 2017) which is related to medial PFC activation (Lane et al. 2001) – ultimately providing a more comprehensive view of not only the subjects’ performance, but also engagement and withdrawal from assessments.

To our knowledge, no prior study has investigated the physiological determinants of run scoring rate in skilled batters. Data presented in this thesis, however, is limited by a few factors. Statistical power is limited by the sample size (total $n = 14$) which were also unbalanced between innings variants (11 v 13). Linear mixed effects models compensate for unbalanced sample groups, and are robust with small sample sizes (Muth et al. 2016). But, some variables could not be modelled for random intercepts and gradients. Cognitive variables from the CogState test battery were restricted to repeated measures analysis of variance, thus reducing the sample size to only subjects that completed both innings’ variants ($n = 10$). If research cannot be affiliated with local high-performance institutes/teams for mutual benefit, recruitment and retention of batters volunteering for assessments conducted over several days presents a considerable challenge.

The logistical challenges are reiterated when mentioning the lack of live bowlers in this investigation. Deliveries projected from a mechanical bowling machine disregard the pertinent kinematic cues that batters are known to perceive from the bowlers action (Cork, Justham, and West 2010; Sarpeshkar and Mann 2011). Therefore, a cognitive component of batting is omitted, and batters intercept deliveries solely from stimuli of ball-flight (Renshaw et al. 2007). The cognitive workload of prolonged batting is conceivably altered if deliveries are intercepted against several live bowlers, their unique kinematic actions, and deceptive variations. Opposed to mechanically projected deliveries which are inherently similar throughout the innings/simulation. Future studies should consider how to investigate the full complement of stimuli that batters process, but factor for the variability that live bowlers will introduce between sessions.

6.4 Conclusion

The physical workload of Twenty20 batting has been sparsely studied. The data presented in this investigation is the first to measure physiological responses of batters directly and holistically throughout a simulated Twenty20 innings directly. Further, chapter II provides methodology, data and software (see appendix 6.4), to develop additional innings simulations which target novel objectives of run totals, scoring rates etc. providing more scope to investigate Twenty20 batting. The peak intensity of a Twenty20 innings appears similar to that of the longer 50-over format. But unlike an ODI innings (Goble and Christie 2017), there is no respite in intensity during the middle overs of an individual Twenty20 innings (Figure 3.3, Figure 3.1)

Our results suggest that skilled batters are more susceptible to executive errors in strategising/planning at high run scoring rates. Although high run scoring intensities increase the physical outputs needed per delivery, skilled batters may employ executive control of exertion (pacing) to maintain prolonged batting performance (Christie et al. 2018; Venhorst, Micklewright, and Noakes 2017). Resultantly, parameters of physical stress may be marginally dissimilar between comparable innings with discrepant striking rates. Adequate pacing, however, may be necessary to preserve cognitive bandwidth for ball-striking aptitude, where exceedingly high physical stress would excessively downregulate pertinent executive functions (Jung et al. 2022). Strategising errors include the executive control of attentional mechanisms inappropriately biasing the representation of expected stimuli, and subsequent motor-responses/strokes (Chun and Marois 2002). Thus, it is conceivable that the heightened standards of desirable interceptions and increased executive control of exertion - compounds the cognitive challenge of batting at high striking rates. The combined cognitive and physical stress modulates the cognitive capacity of the batter, and ultimately high-order, executive functioning is hindered. Elite batters may therefore be most accustomed to the combined stressors of Twenty20 batting. Derived from well-learned pacing strategies and advanced batting-specific physical conditioning (Scanlan et al. 2016) enabling robust, astute cognitive functioning that is most transferable to run scoring performance throughout an innings. For skill development, it is important then to ensure adequate opportunity for athletes to learn pacing strategies and navigate run scoring demands under suitable physical stress.

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Appendices

Plagiarism Report

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A. Ethical Clearance Phase 1-2



R14/49 Tiago Lopes et al

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)**CLEARANCE CERTIFICATE NO. M180872**

NAME: Tiago Lopes et al
(Principal Investigator)
DEPARTMENT: Physiology
 Faculty of Health Sciences

PROJECT TITLE: Cognitive, cardiovascular and muscular strain imposed by
 Twenty20 batting simulations

DATE CONSIDERED: Ad Hoc

DECISION: Approved

CONDITIONS: A sub-study under primary study M171165 - Dr. David Goble

SUPERVISOR: Dr David Gobe

APPROVED BY:

 Professor CB Penny, Chairperson, HREC (Medical)
DATE OF APPROVAL: 30/08/2018

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on the Third Floor, Faculty of Health Sciences, Phillip Tobias Building, 29 Princess of Wales Terrace, Parktown, 2193, University of the Witwatersrand. I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report.** The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. In this case, the study was initially reviewed in **August** and will therefore be due in the month of **August** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).

Principal Investigator Signature

Date

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

B. Information Sheet Phase 2

APPENDIX: Letter of Information

Principal Investigator

Tiago Lopes

Mobile: 083 927 3255

tflopes94@gmail.com

To whom it may concern

We (Tiago Lopes, David Goble, Samantha Kerr and Benita Olivier) are conducting a study on cricket batting performance to better understand the factors that contribute to batting success and those factors that impair batting performance. In particular, we are interested in 20-over cricket matches and how both high- and low-intensity batting affects batters' performance. An area of specific focus is to understand how brain functioning (cognition) is affected by these intensities.

We would like to invite you to participate in the current study entitled, "**Cognitive, Cardiovascular and Muscular Stress Imposed by a Twenty20 Batting Simulation**". Should you consent, your time and efforts are greatly appreciated. The aim of the current investigation is to determine how cognitive performance and physical responses are affected by a simulated batting protocol, where the reliability and validity of the batting simulation will also be assessed. Participation in this study will require you to partake in two phases. The first is an introductory session and the second, the experimental sessions. *You should note that your participation is voluntary and if at any stage you feel you do not want to continue the experiment, you may withdraw/discontinue your participation at any time- this will involve no penalty or loss of benefits to which you are entitled.*

Introductory session (approximately 40 Mins).

The requirements in this initial session are minimal, and acts purely as a basis for me to explain the protocol and, should you agree, I will ask you to sign a consent form. Thereafter, the purpose of the session will be to measure your personal characteristics (e.g. playing history, height, mass, body fat percentage). Following this, an explanation

B. Information Sheet Phase 2

of the testing procedure and what the study aims to achieve will be given to you. The session will require approximately 40 minutes of your time. I will conduct the following measures on you: stature and mass, skin fold analysis, age, ethnicity, player history and other cricket-specific information, visual acuity, and hand-eye coordination. Once these measures are complete, you will have time familiarize yourself with the cognitive test battery that you will be completing in the experimental session. You will be required to complete two baseline assessments of this protocol, after which I will ask you a series of questions to gauge your understanding of each task. Lastly, I will explain to you, exactly how the batting simulation will be run and what is required of you as a batter.

Experimental sessions (each approximately 1hr 30mins)

This stage of the investigation requires two sessions (separated by a minimum of one week) that will be physically and cognitively demanding for you. In these sessions you will be required to complete the same goal-directed cricket outcomes, however, the intensity of each session will vary (high- vs. low-intensity). In each session you will bat for a total of 14 overs (wearing full protective cricket kit) and will be facing a bowling machine set at 120 km.h⁻¹. We will assess cognitive function and muscular power before and after batting, and all other variables (see below) while you are batting. In addition to these measurements, I will obtain a drop of blood from a pinprick of your index finger before and after your batting session to monitor your performance-related changes during experimentation. During each session you will be required to complete sprints between the wickets (along a demarcated pitch of standard length (17.68 m) in the following formats; ones (single shuttle), two's (double shuttle), threes (triple shuttle) and fours (one and a half shuttles).

From the above experimentation I will be measuring the following performance variables; physical performance (sprint times, batting accuracy and vertical jump height), physiological responses (heart rate, heart rate variability and ratings of perceived exertion) and cognitive performance (psychomotor function, visual attention, vigilance, visual learning & memory as well as attention and working memory). Upon completion of the experimentation and data analysis, I will willingly discuss your results with you, thereby sharing the knowledge gained with you.

B. Information Sheet Phase 2

Please note that any information obtained in the experimental sessions will be kept confidential and at no stage or time will any of your personal information be used or publicised. While these efforts will be meticulous, absolute confidentiality cannot be guaranteed and personal information may be disclosed if required by law. The data that will be collected during experimentation will be used only for statistical analysis. All data that is recorded will be given a unique code negating the use of names. This data will be kept for a period of five years, thereafter it will be discarded. Moreover, one copy of the data will be kept in the School of Physiology and may be used for teaching or research purposes and results may also be presented at conferences and published in academic journals. In each instance the names of participants will not be publicised.

While there are minimal risks to you as a participant, there is the inherent risk associated with being a cricket batsmen such as being hit by one of the cricket balls that are projected from the bowling machine. To minimise this risk, you will be dressed in full cricket equipment including a helmet. Additionally, you may experience discomfort (physiological strain) while completing the shuttle running. In light of this I remind you that you are free to withdraw from the study at any stage, without prejudice.

Summary of Participant Requirements

- Attend 3 sessions (one introductory and two experimental sessions).
- Sessions separated by two weeks (subject to participants schedule and availability)
- Habituation session = 40mins
- Experimental sessions = 1hr 30 min
- Full protective cricket kit and bat (bat that can be used with bowling machine)
- Reliability

If there are any queries that you may have, feel free to contact me. Further, should you feel that you have been mistreated in any way, please feel free to contact a neutral party at the School of Physiology or the Wits University Human Research Ethics Committee (Medical) on the details below.

Yours sincerely

B. Information Sheet Phase 2

Tiago Lopes

School of Physiology details

Tel: (011) 717 2363

Lynne.Pritchard@wits.ac.za (secretary)

Wits University Human Research Ethics Committee

Tel: (011) 717 1252/2700/1234/2656

zanele.ndlovu@wits.ac.za

C. Consent Form and Demographics Phase 2



EXERCISE PHYSIOLOGY LABORATORY, SCHOOL OF PHYSIOLOGY
Faculty of Health Sciences, University of the Witwatersrand
7 York Road, Parktown, Johannesburg, South Africa, 2193
Tel: +27 11 717 2363, Fax: +27 11 643 2765

CONSENT TO ACT AS PARTICIPANT IN RESEARCH

I..... (Name and surname) being 18 years or older, consent to participating in a research project entitled: **"A holistic investigation into batting-related performance measures and cognitive responses"**.

The procedures have been explained to me and I understand and appreciate their purpose, any risks involved, and the extent of my involvement. I have read and understand the attached information leaflet.

I understand that the procedures form part of a research project, and may not provide any direct benefit to me.

I understand that all experimental procedures have been sanctioned by the Committee for Research on Human Subjects, University of the Witwatersrand, Johannesburg.

I understand that my participation is voluntary, and that I, as a participant, am free to withdraw from the project at any time without prejudice.

Name and signature of participant

Date

Name and signature of investigator

Date

C. Consent Form and Demographics Phase 2

A

Demographic and Anthropometric Data Sheet

Name		Sex	M	F
Date		Batting Stance	R	L
Age		Current Batting Order		
Resting HR		Glasses		
Stature		Email		
Body Mass		Contact Number		
Body Mass with Kit		Parents Email		
Body Fat %		Parents Contact		

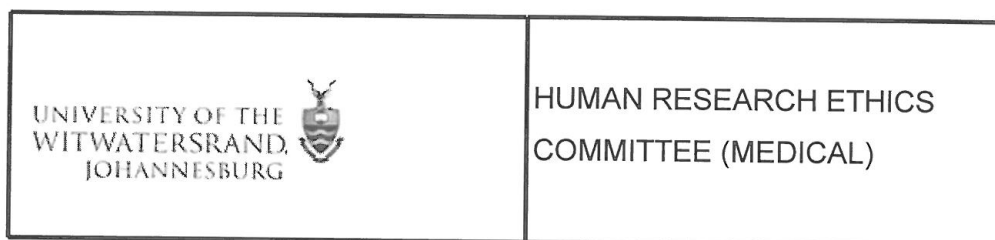
Cricket History

Year Started		Age Started		
Years Played		Player Classification	BAT	A/R
Cricket Played (i.e. club)				
Private Coaching				
- no. of years				
Main Sport Played		Cricket Injuries		
Other Sports Played				
Frequency of Sport				

Medical History

Circle the following diseases or disorders that you have suffered from in the past or are presently					
Heart Problems	Y	N	Migrane	Y	N
High/low Blood Pressure	Y	N	Eye Problems	Y	N
Epilepsy	Y	N	Hypoglycemia	Y	N
Anemia	Y	N	Diabetes	Y	N
Asthma	Y	N	Hyperthyroidism	Y	N
Emphysema	Y	N			
Circle the appropriate response			Frequency		
Do you smoke?	Y	N	> 40	20 - 40	10 - 19
Do you exercise?	Y	N	> 2	3 - 4	4 - 5
Shortness of breath	Y	N			
Chest Pains	Y	N			
Other Sports Played	Rugby		Soccer		Hockey
	Jogging		Squash		Swimming
	Gym		Fitness		Water Polo
Are you currently on any medication?					
Other concerns, medical or otherwise worth mentioning?					

D. Ethical Clearance Phase 3



Dr David Goble, et al
School of Physiology
Medical School
University

12/06/2021

Sent by e-mail to: 750256@students.wits.ac.za

Dear Mr Lopes

Re: Protocol Ref No: M171165

Protocol Title: *A holistic investigation into batting-related performance measures and cognitive responses*

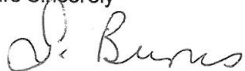
Principal Investigator: Dr David Goble, et al

Thank you for your letter of 23/02/2021 .

I confirm that we have noted and approve of your proposal to recruit additional participants to validate the recording accuracy of your novel device.

Thank you for keeping us informed.

Yours Sincerely



.....
Mr I Burns
For the Human Research Ethics Committee (Medical)



.....
Dr CB Penny, Chairperson, Human Research Ethics Committee (Medical)

E. Information Sheet and Consent Phase 3

School of Physiology

Faculty of Health Sciences, University of the Witwatersrand, Johannesburg
7 York Road, Parktown, 2193 · Tel: +27-11-717-2363 · Fax: +27-11-643-2765



Principal Investigator

Tiago Lopes

Mobile: 060 540 5392

Email: 750256@students.wits.ac.za

We (Tiago Lopes, Samantha Kerr and Benita Olivier) are actively researching cricket batting performance to investigate the factors that contribute to batting success or impair performance. In particular, we are interested in 20-over cricket matches and a specific focus is to understand how brain functioning (cognition) is affected by batting.

We would like to invite you to participate in a study of a novel device we have developed which measures cricket-specific cognitive performance however you do not need to be a cricket player to be involved. The aim of the current investigation is to validate the recording accuracy and precision of this device. Participation in this study will require you to attend a single session in the Movement Physiology Research Laboratory. Should you consent, your time and efforts are greatly appreciated.

Your involvement will require approximately 1 hour of your time and little to no discomfort. The novel device measures your reaction times to visual stimuli. For use in cricket, the visual stimuli are presented on a mock cricket pitch and your inputs are performed by moving your bodyweight with forward or backward strides according to the appropriate stimuli. While you perform this task a slow-motion camera will record your legs to precisely analyse the timing



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of your inputs and the calculations of the device. None of your identifiable features will be recorded. Thereafter, you will perform a similar computer based tasks which measures your reaction times to visual stimuli with your inputs on the keyboard. Finally, we will collect anthropometric variables of mass, height and handedness (side dominance). Please note that any information obtained in the experimental sessions will be kept confidential and at no stage will any of your personal information be used or publicised. The data that will be collected during experimentation will be used only for statistical analysis. All data that is recorded will be given a unique code negating the use of names.

We will also take measures to ensure COVID-19 protocols are strictly adhered to which includes; sanitising all equipment before and after use, the use of Personal Protection Equipment (PPE), and social distancing of 2.5 meters whenever possible.

Thank you for considering your involvement in our research.

We have obtained approval for this study from the Human Research Ethics Committee (HREC) of the University of the Witwatersrand whose contact details are listed below*. Participation in this study is voluntary and you are allowed to withdraw at any time. There will be no payment, or direct personal benefit from participating in the study, as well as no penalty for refusing to take part, or for subsequent withdrawal from the study or from completing the questionnaire. If after reading this information sheet you decide against participating in the study, please be assured that this will not impact on you negatively in any way. If you have further questions, please do not hesitate to ask.

Yours sincerely,

Tiago Lopes



E. Information Sheet and Consent Phase 3

School of Physiology

Faculty of Health Sciences, University of the Witwatersrand, Johannesburg

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* This study has been approved by the Human Research Ethics Committee (Medical) of the University of the Witwatersrand, Johannesburg ("Committee"). A principal function of this Committee is to safeguard the rights and dignity of all human subjects who agree to participate in a research project and the integrity of the research.

If you have any concern over the way the study is being conducted, please contact the Chairperson of this Committee who is Dr Clement Penny, who may be contacted on telephone number 011 717 2301, or by e-mail on Clement.Penny@wits.ac.za. The telephone numbers for the Committee secretariat are 011 717 2700/1234 and the e-mail addresses are Zanele.Ndlovu@wits.ac.za and Rhulani.Mukansi@wits.ac.za

Thank you for reading this Study Information Sheet

CONSENT TO ACT AS PARTICIPANT IN RESEARCH

I, _____ (full name and surname)
agree to participate in the study titled: *Cognitive, cardiovascular and muscular stress of simulated Twenty20 batting innings*

The procedures/questionnaires have been explained to me and I understand and appreciate their purpose, any risks involved, and the extent of my involvement. I have read and understand the attached information sheet.

I understand that the procedures form part of a research project and may not provide any direct benefit to me.

I understand that all experimental procedures have been sanctioned by the Committee for Research on Human Subjects, University of the Witwatersrand, Johannesburg.

I understand that my participation is voluntary and that I am free to withdraw my participation from the project at any time without prejudice.



E. Information Sheet and Consent Phase 3

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Patient name and signature

Date

Investigator name and signature

Date



F. Title Page Published Article Phase 1

METHOD ARTICLE

Novel Twenty20 batting simulations: a strategy for research and improved practice
[version 1; peer review: 2 approved with reservations]

✉ **Tiago Lopes** ¹, David Goble¹, Benita Olivier¹, Samantha Kerr ¹

 [Author details](#)

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Version 1 21 May 21	 read	 read

1. **Sean Muller** , Federation University Australia, Mount Helen, Australia
2. **Habib Noorbhai** , University of Johannesburg, Johannesburg, South Africa

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Abstract

Twenty20 cricket and batting in particular have remained vastly understudied to date. To elucidate the effects of batting on the batter, tools which replicate match play in controlled environments are essential. This study describes the development of two Twenty20 batting simulations, for a high and low strike rate innings, generated from retrospective analysis of international and domestic competition. Per delivery analysis of probabilities of run-type and on/off-strike denomination produce ball-by-ball simulations most congruent with retrospective competitive innings. Furthermore, both simulations are matched for duration and dictated through audio files. The 'high' strike rate innings requires a batter to score 88 runs from 51 deliveries, whereby 60 runs are from boundaries. Similarly, the 'low' strike rate innings requires a batter to score 61 runs from 51 deliveries, where 27 runs are scored from boundaries. Because batting simulations dictate run scoring outcomes, a method of quantifying a batter's performance from bat-ball contact scores is described. Ten elite batters achieved a mean performance score of 72 (SD = 26) and 88 (21) for the low and high strike rate simulations respectively. This study provides sport practitioners with a training technique to improve specific skill acquisition and enables research in understudied Twenty20 batting.

Keywords

Cricket, batting performance, simulation, innings

✉ Corresponding author: [Tiago Lopes](#)

Competing interests: No competing interests were disclosed.

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The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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How to cite: Lopes T, Goble D, Olivier B and Kerr S. Novel Twenty20 batting simulations: a strategy for research and improved practice [version 1; peer review: 2 approved with reservations]. *F1000Research* 2021, 10:411 (<https://doi.org/10.12688/f1000research.52783.1>)

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Tiago Lopes

Data and code to investigate cricket innings

Files

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 - README.md 1.0 kB
 - Supp.Material.A.m4a 16.6 MB
 - Supp.Material.B.m4a 17.1 MB
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 - T20TOP7.csv 727.2 kB
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